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SUMMARY

The National Aeronautics and Space Administration has recently completed a flight program to evaluate the use of direct lift control (DLC) as an aid to flight-path control during approach and landing. The program utilized a U.S. Navy F8-C airplane modified to incorporate symmetrically variable ailerons to augment the primary longitudinal control system. The airplane was also equipped with an airspeed-sensing autothrottle and a commercially available cross-pointer-type instrument landing system. Approximately 230 approaches were made along various single- and two-segment approach paths, guidance being provided by a modified AN/GSN-5 radar and instrument landing system data link. Comparisons of flight-path deviations and touchdown dispersion between the basic F8-C control system and the direct lift control system were made.

The results indicate that direct lift control provides a better control of small flight-path errors than the conventional F8-C control system. Direct lift control with a controlled pitch attitude change, provided through an aileron to horizontal tail interconnect, improved piloting performance and reduced workload during the approach and landing task.

INTRODUCTION

A need for improved flight-path control during approach and landing is being emphasized by the introduction of larger transport aircraft, lower landing weather minimums, and consideration toward steeper than normal approach angles to reduce noise levels around airports. Research is currently underway to investigate means of providing the pilot with a more rapid and precise control of height during approach than is provided solely by the conventional controls. Candidate augmentation devices include symmetrically variable flaps, spoilers, or ailerons; boundary layer control; and thrust deflection or vectoring.

The U.S. Navy recently conducted some experiments on an F8-C aircraft with symmetrically drooped variable ailerons for longitudinal control (refs. 1 and 2) and results showed that this concept permitted faster correction and, by the same token, smaller deviations in the final approach than the conventional F8-C control system. The Navy tests, however, were directed toward the carrier landing task. In an effort to apply the direct lift control (DLC) concept to the air transport environment and to determine some of the response and trim requirements for direct lift control operation, the Langley Research Center has conducted a flight test program on the F8-C airplane at the NASA Wallops Station. Prior to flight testing, the direct lift control system was modified slightly, based on results of the Navy tests; and a commercial instrument landing system (ILS) was installed. The aircraft was flown along various single- and two-segment approach paths with guidance provided by a modified AN/GSN-5 radar and ILS data link.

This paper presents the results of the F8-C direct lift control flight tests. The data show comparisons of flight-path deviations and touchdown dispersions between the standard F8-C control system, with and without autothrottle, and the direct lift control system, with and without autothrottle. Comments on the effect of center-of-gravity change on trim requirements are also presented.

AIRPLANE AND TEST EQUIPMENT

Airplane

The test airplane is a single-seat production F8-C airplane with a modified aileron control system for direct lift control and an airspeed-sensing approach power compensator. A commercially available cross-pointer-type ILS system was installed to provide guidance during the program. In addition, the aircraft was equipped with flight-recording instrumentation including an instrumented nose boom, a radar corner reflector, and a timing transmitter to correlate flight records with ground radar recordings. A three-view sketch of the airplane is shown in figure 1, and a photograph taken in the landing configuration is presented in figure 2.

Some basic F8-C airplane short-period dynamics of interest are listed for the airplane in the landing configuration.

Period: 8.98 sec – at 19 000 pounds (84 512 N) gross weight and center of gravity at 28.4-percent mean aerodynamic chord

6.03 sec – at 22 000 pounds (97 865 N) gross weight and center of gravity at 24-percent mean aerodynamic chord

Damping ratio: 0.3365

L_{α} (approximates the inverse time constant representing the lag between normal acceleration and pitch rate for elevator inputs): 0.426/sec

Direct Lift Control System

The modified aileron control system controls lift by rapidly varying aileron droop symmetrically in response to pilot-initiated commands from a stick-mounted wheel switch. Symmetrical aileron deflection was proportional to wheel switch deflection. The wheel switch was mounted on the left side of the stick grip, normally occupied by the longitudinal trim control, and was spring loaded to neutral. The trim switch was relocated on the right side of the stick grip. Mechanization of the direct lift control drive system is described in reference 3.

During the Navy evaluation, the pilots objected to not having enough up direct lift control authority to arrest excessive sink rates near touchdown. The Navy system had a neutral position of 15° trailing edge (T.E.) down and a range of travel from 0 to 28.5° trailing edge down. Therefore, for the NASA tests two aileron neutral positions were installed at 12° and 14° trailing edge down. In addition, the total aileron throw was increased from 28.5° to 32°. To determine the effect of direct lift control authority on pilot performance, a selector switch was provided to limit the aileron travel to two-thirds and one-third of the full authority travel. Table I lists the aileron configurations for the basic F8-C, the Navy direct lift control, and the NASA direct lift control systems in the landing configuration.

Differential aileron travel was retained on the control stick for roll control. However, during full "up" or "down" DLC inputs, roll control authority was limited to approximately 50 percent of that for the basic airplane. (See ref. 1 for discussion of lateral control surface rigging.)

Aileron to tail interconnect.- A variable gain interconnect between the aileron droop and the pitch trim actuator of the all-movable horizontal tail was provided to modify the pitching moment resulting from a direct lift control input. The interconnect gain was controlled by a dc potentiometer in the cockpit and provided the variations of tail deflection with aileron droop position shown in figure 3. The pitch trim actuator could deflect the horizontal tail at a maximum rate of 3.5° per second. The gain numbers shown represent the cockpit dial settings and have no significant meaning other than that increased tail deflection is associated with increasing numbers.

Autothrottle

The airplane was equipped with an airspeed sensing autothrottle or approach power compensator (APC). Records show that the autothrottle maintained airspeed within ±5 knots of the reference speed during most of the autothrottle approaches. In a few instances, however, turbulence during the approach caused the airspeed to exceed 5 knots above the reference because the approach power compensator could not reduce the power below 75 percent of the engine design speed.

Instrumentation

Airborne.- Airborne instrumentation used for documenting performance during the flight test program consisted of a 24-channel 8-inch oscillograph and a photo-observer. The parameters and sensitivities as recorded on the oscillograph are given in the following table:

Oscillograph channel	Condition	Sensitivity
1	Open	------------
2	Longitudinal acceleration	0.21 g/in.
3	Right aileron position	17.53°/in.
4	Left aileron position	17.6°/in.
5	Pitch attitude	7.83°/in.
6	Normal acceleration, coarse	1.71 g/in.
7	Altimeter (sensitive)	210 ft/in.
8	Throttle position	30°/in.
9	Direct lift control actuator position	0.918 in./in.
10	Pitch trim position	11°/in.
11	Direct lift control trim potentiometer position	13 volts/in.
12	Normal acceleration, sensitive	0.263 g/in.
13	Longitudinal stick position	11.56°/in.
14	Lateral stick position	20.57°/in.
15	Bank angle	50°/in.
16	Roll rate	50°/sec/in.
17	Pitch rate	9.45°/sec/in.
18	Angle of attack (noseboom)	5.125°/in.
19	Angle of attack (production)	8.24°/in.
20	Airspeed recorder	24 knots/in.
21	Rudder position	19.5°/in.
22	Horizontal tail interconnect	13.2 volts/in.
23	Horizontal tail position	11.3°/in.
24	Correlation	------------

Parameters recorded by the photo-observer were:

Noseboom altitude
Noseboom airspeed
Angle of attack, production

Total turbine outlet pressure at station seven
Low pressure compressor rotor speed
High pressure compressor rotor speed

Ground based.- Ground-based instrumentation consisted of a modified AN/GSN-5 radar unit to provide flight-path guidance to the aircraft and to measure and record aircraft performance. To provide guidance to the aircraft, the radar unit determined the position of the airplane relative to a preset glide slope and then transmitted proportionate slope deviation and course deviation signals to the airplane.

The AN/GSN-5 has an antenna beam width of approximately $1/2^{\circ}$ with an angular tracking capability of -10° to 30° in elevation and $\pm 45^{\circ}$ in azimuth. It was capable of determining airplane position both in rectangular coordinates and with respect to a selected glide slope. The glide slope can be set at a range of values up to 15°.

Time histories were recorded of the following parameters: range, range rate, altitude, altitude rate, glide-slope error, and localizer error. In addition, plots of the variation of range with altitude and of range with localizer error were made.

TEST CONDITIONS

Four airplane configurations were used during the test program:

Standard F8-C control system
Standard F8-C control system with autothrottle
Direct lift control
Direct lift control with autothrottle

Approach Profiles

Two basic profiles were used during the program – one a 6° single-segment approach with a smooth curved flare from 200 feet (61 m) to touchdown and the other a two-segment 6° to 3° approach with a transition between the two angles and no flare guidance to touchdown. A sketch of the profiles is shown in figure 4. Average transition or flare rates of $\frac{1}{3.5}$ $^{\circ}$/sec and $\frac{1}{7}$ $^{\circ}$/sec were used for most of the program. In addition, a step transition, illustrated in the insert of figure 4, was used which gave an instantaneous change to the 3° portion about 50 feet (15 m) above the normal intersection of the 6° and 3° paths. Normal intersection occurred at approximately 800 feet (244 m) altitude.

Normal instrument landing system sensitivities of 0.7° for 150 milliamperes or full deflection of glide slope and 2.5° for full deflection of localizer were used for the approach evaluation.

The Piloting Task

All approaches were made under visual flight conditions with a chase airplane to monitor the test airplane and insure that the area remained clear of aircraft. Glide-slope intercept was at approximately 2500-foot (762-m) altitude and 5-mile (8-km) range on all two-segment approaches and 3000-foot (914-m) altitude and 5-mile (8-km) range on the single-segment 6° approach. Although the pilot was not hooded, he attempted to fly the profiles on instruments only to 100-foot (30-m) altitude; at this point, transition was made to visual conditions to execute the final flare and touchdown. A painted target on the runway 1500 feet (457 m) from the threshold served as the intended touchdown point. Cockpit guidance for the profiles was in the form of raw instrument landing system deviation presented on a standard instrument landing system cross pointer indicator. It should be noted that, as with a normal instrument landing system, the error signals displayed to the pilot were in terms of angular deviation. Thus, the display became more sensitive as the airplane proceeded down the glide slope. Correspondingly, a given deviation indication meant a much larger absolute error at glide-slope intercept than when near the runway.

DOCUMENTATION OF AIRCRAFT RESPONSE TO DLC INPUTS

Prior to the actual approach evaluations, several flight hours were provided for the pilot to select the best direct lift control configuration for the approach and landing task. As a result, the 12° neutral position with full authority (0 to 32° aileron travel) and an aileron to tail interconnect gain of 12 were selected. The 12° neutral position provided the pilot with slightly more upward direct lift control authority than downward and appeared to be desirable for arresting sink rates at touchdown. The full-authority mode was found to be adequate in calm air; however, even more authority would be desirable for moderate or greater turbulence conditions. The interconnect gain of 12 was chosen because it was the only gain setting that provided a significant pitch-down with downward direct lift control. The pitch-up with upward direct lift control was somewhat higher than desired but was acceptable.

Figure 5 presents, in time history form, the response of several parameters to upward and downward direct lift control inputs both with and without autothrottle for the selected configuration. The inputs were initiated with the airplane in trimmed level flight and held in for 4 seconds or more. For an upward command, the direct lift control input induces an initial acceleration of about 0.1g at the center of gravity. The time rise of the acceleration nearly matches the droop time of the ailerons. There is no significant pitch-attitude change until about 1 second after the input is applied after which the airplane begins to pitch up at a rate of about 2.8° per second with the autothrottle on and about 2°

per second with the autothrottle off. Angle of attack during this period varied approximately $\pm 1.0^{\circ}$. Normal approach angle of attack was approximately 13°.

From the radar plots of height change against time, the aircraft climbs about 20 feet (6 m) in 3.5 seconds after a full up command and descends about 15 feet (5 m) in the same time after a down command.

Acceleration response.- Figure 6 shows the variation of the peak initial normal acceleration with airspeed for direct lift control inputs of full, two-thirds, and one-third authority. For full authority (fig. 6(a); 0 to 32° aileron travel) inputs from the 12° neutral position, the mean peak acceleration was 1.1g for an up direct lift control command or 0.1g incremental from the 1.0g level flight acceleration. For a down direct lift control command the mean value was 0.913g or -0.087g incremental g. Although there is considerable variation in the data shown, there is no trend toward increasing or decreasing acceleration with speed.

For a two-thirds authority (4° to 24° aileron travel; fig. 6(b)), the mean incremental values of normal acceleration were 0.07g and -0.06g for up and down inputs, respectively. With a one-third authority (fig. 6(c)), the mean values were +0.047g and -0.033g.

Pitch response.- The pitch attitude response to a direct lift control input was found to be dependent on both the aileron to tail interconnect gain and the center-of-gravity location on the airplane. The center-of-gravity range for the airplane extended from 22 to 36 percent mean aerodynamic chord. Figure 7(a) presents time histories of pitch response for three gain settings with the airplane in the mid to forward center-of-gravity range (23 to 26 percent). Without any interconnect (gain = 0), the airplane pitched up following both up and down direct lift control commands. The pitch-up with up direct lift control was probably a result of increased downwash on the horizontal tail as the aileron droop increased. A gain of 10 provided what the pilot felt to be the most desirable response for an up command, but the airplane did not pitch nose down following a down direct lift control command at this setting. As stated earlier, a gain of 12 was selected for use in the approach evaluations because of the downward pitch response.

Figure 7(b) presents similar time histories for the airplane configured in the aft center-of-gravity range (29 to 32 percent mean aerodynamic chord). In this aft range, the pilot was unable to select a single gain setting that would provide acceptable pitch response to both up and down direct lift control inputs. With a gain of 12, the pitch-down with down direct lift control was similar to that of the forward center-of-gravity range. For an up direct lift control command, however, a gain setting of 2 was required to nearly match the desired forward center-of-gravity response obtained from a gain setting of 10. Therefore, for satisfactory operation of direct lift control on this aircraft over the entire center-of-gravity range, it would be necessary to shape the interconnect gain variation as a function of both the center-of-gravity position and aileron deflection.

PRESENTATION OF RESULTS

The results of the flight tests are presented in three basic categories: (1) direct lift control utilization, (2) approach performance, and (3) landing performance. Direct lift control utilization describes the intermix between this direct lift control system and the standard controls for the approach and landing task. Approach performance deals with the results obtained during that portion of the approach between glide slope intercept and approximately 100-foot (30-m) altitude wherein the pilot is attempting to fly on instrument information only. Touchdown performance deals with the task of the pilot landing on a target marked on the runway.

All data presented in this section refer to the aircraft in the middle to forward center-of-gravity configuration and with an aileron to tail interconnect gain setting of 12.

After the presentation of data for each category, a section of pilot comments is included to provide subjective discussion on the application and the use of the specific direct lift control system tested.

Direct Lift Control Utilization

Flight results.- Figure 8 presents plots of longitudinal stick position and direct lift control command position for three approaches. The upper two approaches – one standard and one direct lift control – were made in smooth air whereas the lower direct lift control approach was made in turbulent air. Comparing the relative control activity between the approaches gives an indication of the pilot's use of the direct lift control system for the approach task. In calm air, use of direct lift control resulted in a significant reduction in both frequency and amplitude of the longitudinal stick activity. In turbulence the stick activity is reduced only slightly in frequency from the standard approach in calm air; however, the amplitudes of the stick deflections are again reduced considerably. Comparing the direct lift control commands or thumb controller position shows that the pilot used more partial authority control during the smooth air approach than in turbulence. It is also interesting to note that the length of the direct lift control inputs decreases as the aircraft approaches the runway. It is felt that from about 100-foot (30-m) altitude to touchdown, the pilot used short-term direct lift control inputs (≤ 1 sec) to obtain the desired flight path without changing attitude, or in effect, separated the short-term direct lift control response from the longer term (>1 sec) pitch response and controlled pitch attitude with the control stick.

The pilot indicated during the program that the approach task could be performed by using only the direct lift control controller. Therefore, on five approaches a quick disconnect chain lock was attached between the control stick and the pilot's seat and the approaches were flown with direct lift control only. Figure 9 shows a time history of one approach made with the chain stop connected. The chain stop was disconnected prior to the final flare as a safety precaution in view of the limited authority of the direct lift control system. With the direct lift control system used as the primary control, the pilot made fewer inputs during the approach than when both the direct lift control and normal controls were available. Comparing the glide slope error with the direct lift control command shows that the commands are generally in the correct direction to return to the glide slope. This result indirectly indicates that the pilot had fairly good control of the pitch response by varying the duration of the inputs and, as a result, required fewer control reversals to check excessive pitch attitudes or rates.

Pilot comments on direct lift control utilization.- When attempts were made to obtain maximum precision in instrument-landing-system glide-slope performance, it quickly became apparent that the desired technique of direct lift control employment was markedly different at the extremes of glide-slope sensitivity, consisting of long-term inputs (>1 sec) in the insensitive glide-slope region and short-term inputs ($\leq$1 sec) as the airplane approached the runway. This method of differentiating between two types of control technique is meant to apply only generally, since a combination of the two was almost always employed; use of these terms refers to the technique used more frequently.

Long-term control inputs: The glide slope was intercepted by using normal flight controls and the airplane was trimmed in pitch. From this point, the direct lift control controller was effective for glide-slope control, employed as a pitch controller rather than as a lift controller. In smooth atmospheric conditions, the small pitch rates occurring 1 to 2 seconds after direct lift control input aided significantly in improving glide-slope precision when combined with a small amount of primary pitch control movement, with autothrottle engaged. In turbulence, the improvement offered by direct lift control was degraded; more primary control movement was required to counteract pitch upsets. The improvement afforded, however, was still sufficient to warrant its use. Further, under smooth conditions the use of varying input levels was desirable whereas turbulence usually resulted in full "bang-bang" inputs, again employed to counteract pitch upsets.

Short-term control inputs: As the airplane entered the more sensitive glide-slope region, defined here as below 200-foot (61-m) altitude, the value of small quick-response flight-path changes afforded by direct lift control as such became apparent. Thus, shorter term inputs were used, partly to avoid the pitching effects of longer term inputs and partly because of the smaller absolute errors involved. It should be emphasized that the direct lift control pitching effects were still being utilized for glide-path control although in a much more restricted manner than had been the case in the more insensitive glide-slope region. Turbulence had the same effect as previously described. At an altitude of 50 feet (15 m) to 100 feet (30 m), the transition from instrument to visual flight was made for the task of flaring to a touchdown runway target. The remainder of the approach was conducted by visual reference to the runway by using direct lift control to descend to the touchdown point by the use of a series of "stairstep" maneuvers. Some flight-path curvature existed, of course, but this technique made it possible for the flare to be conducted in a series of small height increments and thus enhanced precise judging of touchdown.

Approach Performance

The method of evaluating approach performance in this program was primarily through comparison of radar plots of glide-slope error or altitude against range for the four airplane configurations. Pilot workload, which enters into the landing task and may not always be reflected in the accuracy of task performance, is also considered to be important and is discussed in the pilot comments.

The adverse wind conditions experienced during the program often made it difficult to single out effects of airplane configuration change on the approach performance. Cross-wind components in excess of 10 knots to the approach path were common and were frequently very turbulent. The test aircraft had a cross-wind limit of 15 knots for landing.

To illustrate the effect of winds and turbulence on approach performance, figure 10 presents composites of glide-slope error plotted against range for 103 approaches separated into categories of steady winds (includes cross winds <10 knots), cross winds ($\geqq 10$ knots), and turbulence (moderate to occasionally severe as reported by the pilot). For the steady winds (fig. 10(a)), there is a slight improvement in approach performance as the aircraft configurations progress from the standard configuration without autothrottle to direct lift control with autothrottle. For steady cross winds $\geqq 10$ knots (fig. 10(b)), the errors for the four configurations are about the same. In turbulence (fig. 10(c)), however, the trend is almost reversed, the standard configuration plus autothrottle having perhaps the least error. The degradation in performance for the direct lift control approaches in turbulence is attributed to two factors: (1) the limited authority of the direct lift control system and (2) an attempt by the pilot to use a minimum of stick control during direct lift control evaluation. These factors resulted in the pilot accepting larger errors before the long-term pitch change of the direct lift control system could begin to correct pitch upsets caused by the turbulence. Lateral, or localizer, deviations were similar for all four configurations.

The following discussion on approach performance is therefore limited to approaches made in less than moderate turbulence as reported by the pilot and less than 10-knot cross wind as measured at the ground radar station.

Performance on the 6° single-segment profile.- Figure 11 shows radar plots of altitude against range for a series of 14 consecutive approaches made on the 6°

single-segment profile with a $\frac{1}{7}$ °/sec flare to touchdown. The standard configuration both with and without autothrottle had somewhat higher deviations from the intercept point through the initial portion of the flare than did the direct lift control configurations. Light turbulence was reported by the pilot throughout this series of runs.

The flare presented no particular difficulty except that the pilot indicated a tendency to drop below the flare path which he attributed primarily to the type of guidance display. This "duck under" is not noticeable in figure 11; however, it has been found to be common for curved profiles and is discussed in more detail in the section on transition rates.

Analysis of the glide-path error on the single-segment 6° approach showed that the pilot was within 1/2 dot of indicator error 53 percent of the time for the standard configuration without autothrottle and 66 percent of the time with autothrottle. For the direct lift control approaches without and with autothrottle the corresponding values were 71.6 percent and 71.8 percent, respectively.

Performance on the two-segment 6° into 3° profile.- Figure 12 presents radar plots of altitude against range for 15 consecutive approaches on the two-segment 6° into 3° profile with a $\frac{1}{3.5}$ °/sec transition. These approaches were conducted on a day with no turbulence and very light winds. In the standard configuration without autothrottle, the pilot negotiated the profile with reasonable precision; however, the deviations are larger than those for the other configurations. The combination of direct lift control plus the autothrottle provided the tightest control throughout the approaches. Analysis of the glideslope error for this series of runs showed that with direct lift control and autothrottle, the pilot remained within 1/2 dot of indicator error 80.5 percent of the time compared with 77.6 percent for direct lift control without autothrottle. Corresponding percentages for the standard configuration were 79.5 percent with autothrottle and 73.7 percent without autothrottle.

Effect of transition rate.- In previous programs to study operational problems of the two-segment approach paths, gentle curved guidance has been provided to aid the pilot during the transition period. These curved transitions were intended to prevent the airplane from dropping below the final approach segment and thereby forfeit some of the noise alleviations provided by the two-segment profile. A basic problem exists with the curved flight path, however, if only instrument landing system error data are displayed to the pilot. During a transition, the pilot will not begin to curve the flight path until an error indicating the direction of change required is displayed. In this program, transition rates of $\frac{1}{3.5}$ °/sec and $\frac{1}{7}$ °/sec (based on 140 knots approach speed) were investigated. In addition, a step transition applied at a point 50 feet (15 m) above the normal intersection of the 6° and 3° paths was evaluated. It was reasoned that an instantaneous display of error from the 3° path would provide the pilot with a more usable information display provided he was aware of the transition. Figure 13 presents radar plots of airplane position with respect to the glide path during direct lift control approaches for the three transition profiles. For the two curved transitions, there is a predominant "duck under" shown before the aircraft stabilizes on the final segment. The "duck under" is almost eliminated in the step transition approaches. In these tests the pilot relied on the jump in the glide-slope needle to indicate that the transition was being made. It is felt, however, that either a light or an audio signal should be provided to alert the pilot in case he should miss the error indicator.

Pilot comments.- The airplane was rather sluggish longitudinally in terms of pitch response to control inputs. Also, stick breakout forces were high, relative to the force gradient. These factors combined to cause a tendency toward overcontrolling in pitch and a technique of checking control stick inputs; these conditions were emphasized as the glide-slope error indication became more sensitive. Although good instrument landing system tracking accuracy could be attained, the associated physical workload was high.

Airplane speed stability was very poor and required a high level of attention to airspeed control by thrust adjustment. The use of an autothrottle was a major factor in reducing pilot workload since more attention could be devoted to flight-path control.

Use of direct lift control further reduced physical workload because of an improved precision of pitch attitude control. In smooth air, direct lift control alone had sufficient authority to control the airplane flight path. The direct lift control authority was limited, however, and this limitation required that the glide-slope errors be kept small. Workload other than that of a physical nature was thus imposed, in that instrument scan pattern had to be adjusted to provide closer attention to the instrument landing system indicator. Accordingly, frequent actuation of the direct lift control thumb controller was required. However, the workload associated with direct lift control operation was preferable to that involved with the basic configuration. Also, precision of instrument landing system performance could be slightly improved with direct lift control.

A limited number of approaches were made with the aircraft center of gravity in the range of 29 to 32 percent mean aerodynamic chord. This aft range was found to be unsatisfactory for the approach task because of the large difference in pitch response between up and down direct lift control inputs.

Landing Performance

The landing performance investigated during the tests include longitudinal and lateral dispersion from the intended touchdown point and impact accelerations. Dispersion data were reduced from photographs of the landings and impact accelerations measured from an accelerometer located near the center of gravity of the airplane. A sketch of the target and its location on the runway is shown in figure 14.

Touchdown dispersion.- Histograms of longitudinal dispersion for the standard and direct lift control configurations are presented in figure 15. For the standard configuration (fig. 15(a)), 57 percent of the landings were within 100 feet (30 m) of the target with a maximum dispersion of about ±500 feet (152 m). For the direct lift control landings (fig. 15(b)), 80 percent of the landings were within 100 feet (30 m) of the target and the maximum dispersion was ±350 feet (106 m). Lateral dispersions shown in figure 16 indicated no significant change between standard and direct lift control landings.

Touchdown accelerations.- The incremental impact accelerations (normal) for the two configurations are shown in figure 17 plotted against touchdown distance. Both configurations showed a trend toward higher accelerations near the intended touchdown point. From histograms of impact accelerations (fig. 18), the mean acceleration for the direct lift control landings was about 0.2g higher (1.7g compared with 1.5g) than the standard configuration landings. Correlations of impact accelerations with airspeed and gross weight showed no recognizable trends.

Pilot comments.- The landing, as discussed here, occurred between an altitude of 50 feet (15.2 m) and touchdown. Although the change from instrument to visual conditions was made at about 100 feet (30 m), radar guidance was utilized until the airplane descended to 50 feet (15 m). From this point there is a usable flare-path envelope to the touchdown target which is established by the airplane sink rate and the response of the airplane to control inputs.

For the basic airplane the envelope was very small. Early arrestment of sink rate was required in order to maintain pitch attitude at landing within the narrow limits of nose wheel first or tail pipe dragging. Thus, even though it became apparent as the airplane neared the ground that the target would be overshot or undershot, there was little that could be done to change the sink rate.

The flare-path envelope was enlarged considerably with direct lift control because of the separate and precise control of flight path independent of attitude. The technique employed was that of "stairstepping" or breaking the flare maneuver into a series of small height increments. The chief constraint was the steepness of the flight path to the target. If the airplane was considerably above glide slope at an altitude of 50 feet (15 m), an overshoot of the touchdown target was usually accepted to avoid setting up a sink rate too large to be quickly arrested by direct lift control.

It was obvious that the sink rates at touchdown were somewhat higher for the direct lift control landings, but they did not seem to be excessively so. Subjectively, the increased sink rate was well worthwhile in view of the improved control of touchdown. In fact, the sink rates were intentionally created in order to touch down on target. Without direct lift control, sink rate could be controlled only by attitude, in the short-term sense. Therefore, the option of increasing the sink rate in order to touch down on target did not exist since associated pitch-attitude changes could not be tolerated near the ground because of the previously mentioned touchdown attitude constraints. It might also be noted that on the final landing for each flight, although data were not recorded, the direct lift control seemed to be very beneficial in "greasing" the airplane on to the runway when no attempt was being made to impact on the target.

CONCLUSIONS

Results of a flight test program to evaluate the use of a specific direct lift control system on an F8-C airplane during approach and landing have led to the following conclusions:

1. Direct lift control provides for better control of small flight-path errors than the conventional control system.

2. Direct lift control with a controlled pitch-attitude change, provided through the aileron to horizontal tail interconnect, is effective in improving pilot performance and reducing workload during approach and landing.

3. Automatic speed control is required for this direct lift control system for use on the instrument landing system glide slope above an altitude of 200 feet (61 m).

4. Control of the touchdown point is more accurate with direct lift control; however, slightly higher impact accelerations were accepted in order to obtain the improved accuracy.

5. For satisfactory operation on approaches under turbulent atmospheric conditions, the direct lift control authority should be greater than that available from the system evaluated (0.1g up authority and 0.087g down authority).

6. Pitch compensation that is related to both center-of-gravity position and aileron deflection is required for satisfactory operation of this direct lift control system over the airplanes usable loading range.

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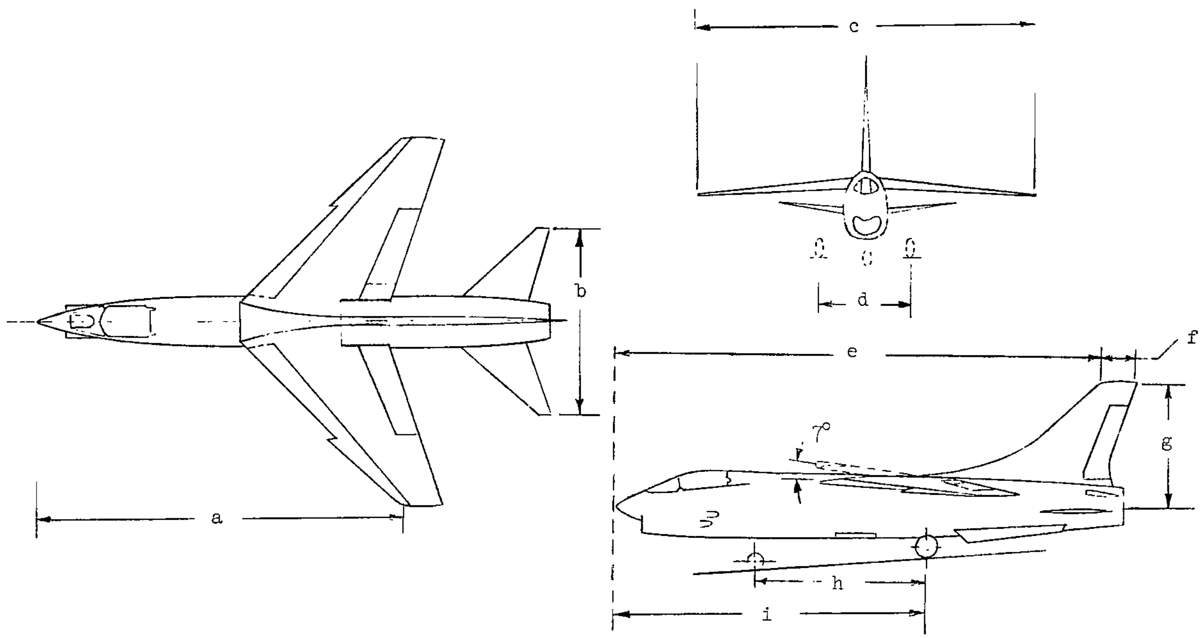
2. Smith, L. R.; Prilliman, F. W.; and Slingerland, R. D.: Direct Lift Control as a Landing Approach Aid. AIAA Paper No. 66-14, Jan. 1966.
3. Etheridge, J. D.; and Mattlage, C. E.: Direct Lift Control as a Landing Approach Aid in the F-8C Airplane. Simulator and Flight Tests. Rep. No. 2-53310/4R-175 (Contract N 62269-2403), LTV Vought Aeronaut. Div., December 13, 1964.

TABLE I.- AILERON CONFIGURATIONS (LANDING CONDITION)

	Basic F8-C	Navy direct lift control	NASA direct lift control with –		
			Full authority	2/3 authority	1/3 authority
Neutral position	20° trailing edge down	15° trailing edge down	12° and 14° trailing edge down	12° trailing edge down	12° trailing edge down
Symmetrical deflection from neutral	--------------------	15° trailing edge up 13.5° trailing edge down	12° and 14° trailing edge up 20° and 18° trailing edge down	8° trailing edge up 14° trailing edge down	4° trailing edge up 7° trailing edge down
Maximum aileron deflection rate for direct lift control operation	--------------------	45°/sec (15° to 28.5°) 37°/sec (15° to 0°)	43°/sec (12° to 32°) 30°/sec (12° to 0°)	43°/sec (12° to 26°) 30°/sec (12° to 4°)	43°/sec (12° to 19°) 30°/sec (12° to 8°)



Dimension	Feet (Meters)
a	38.2 (11.6)
b	18.1 (5.5)
c	35.7 (10.9)
d	9.7 (3.0)
e	50.8 (15.5)
f	3.4 (1.0)
g	12.8 (3.9)
h	18.1 (5.5)
i	32.6 (9.9)

Figure 1.- Three-view sketch of test airplane.

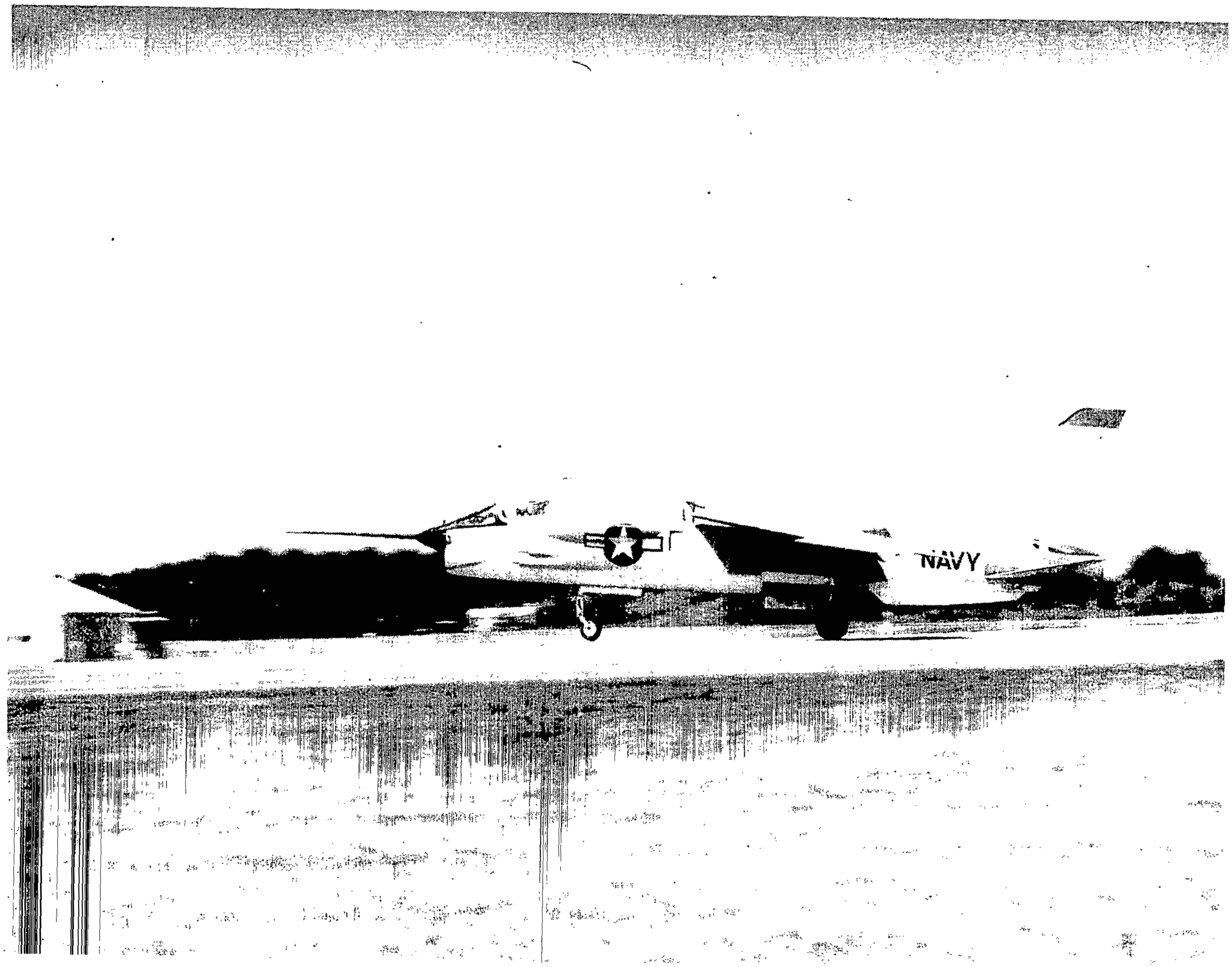


Figure 2.- Photograph of test vehicle in the landing configuration.

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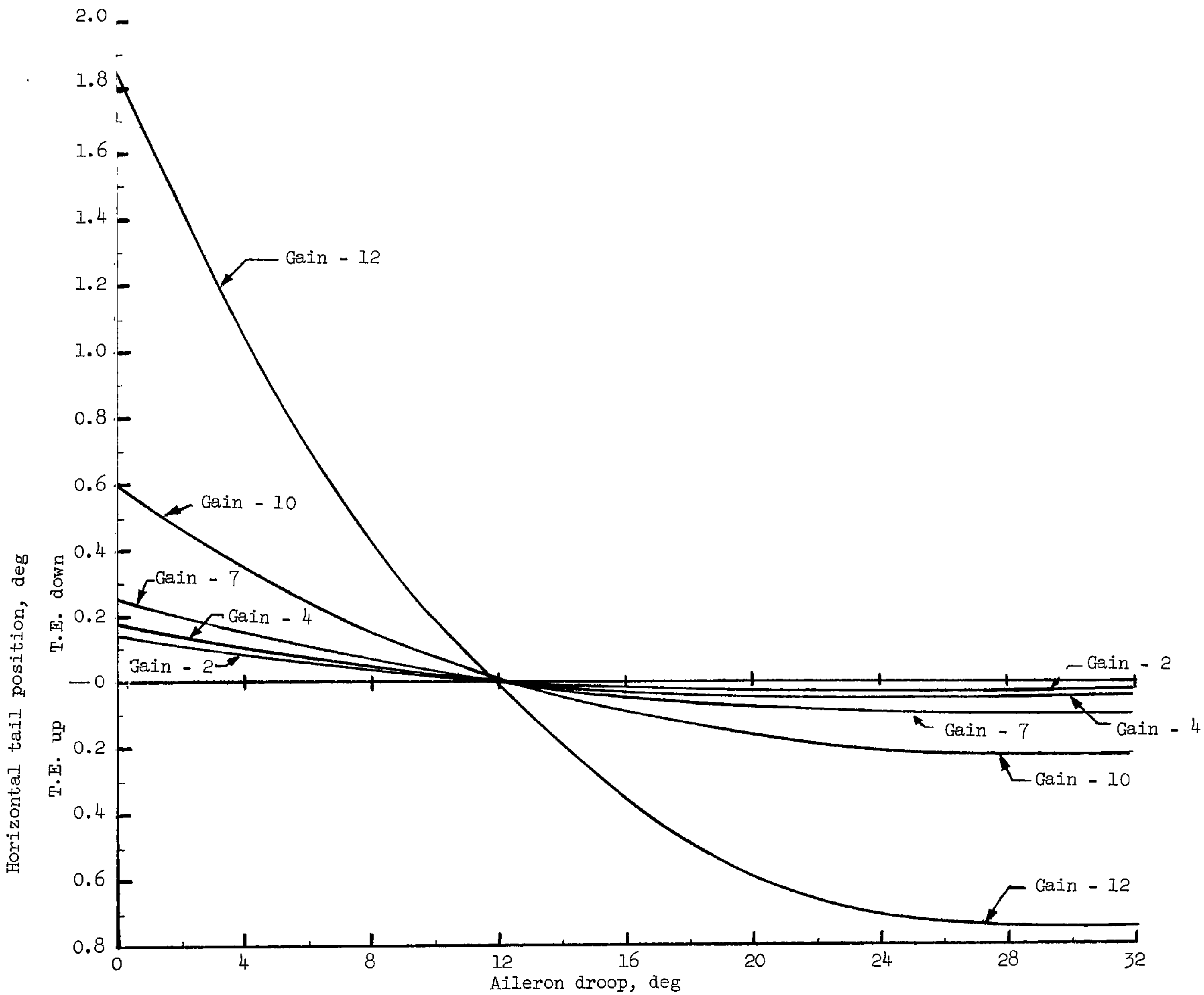


Figure 3.- Variation of horizontal-tail position with aileron droop for different interconnect gain settings.

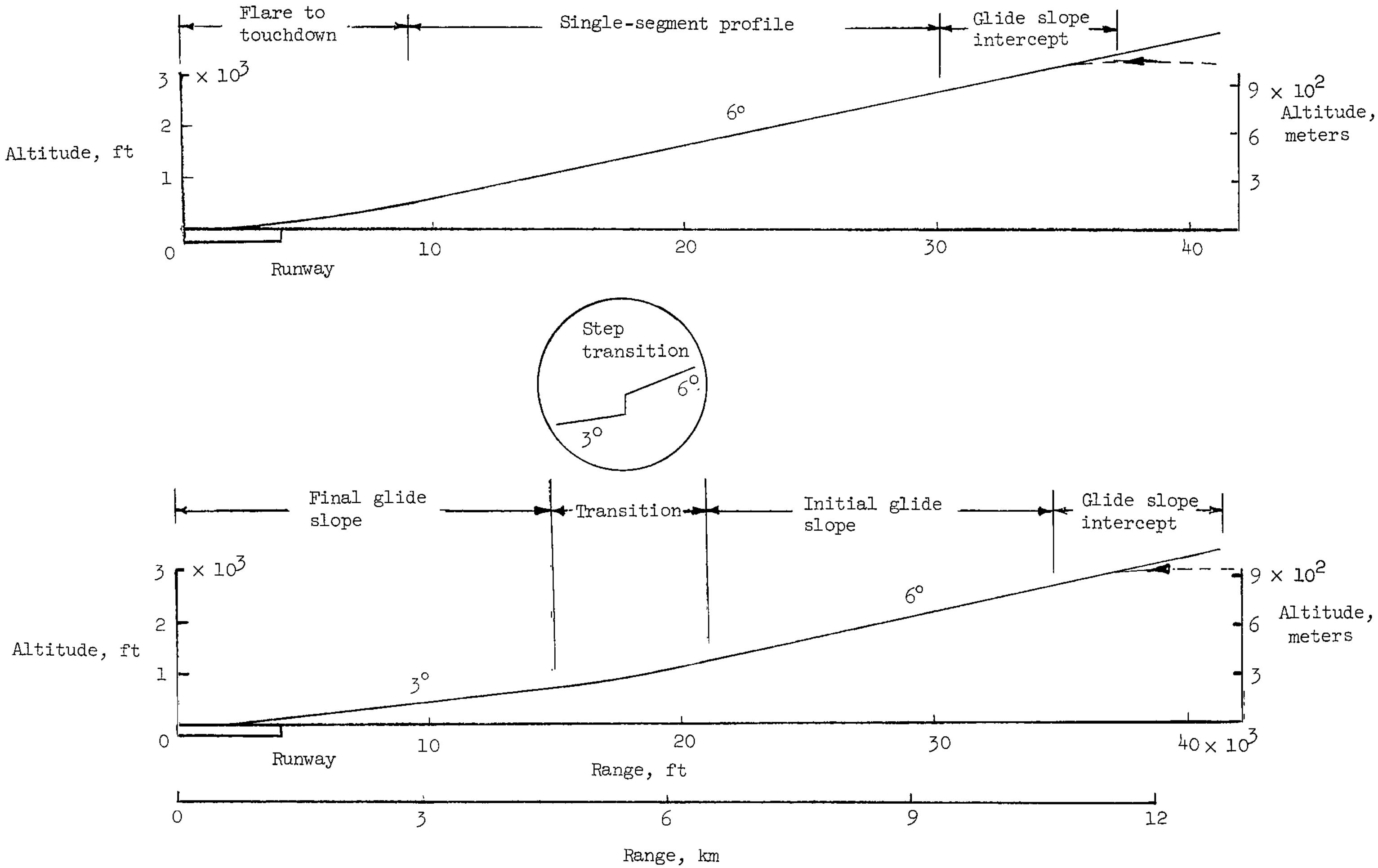
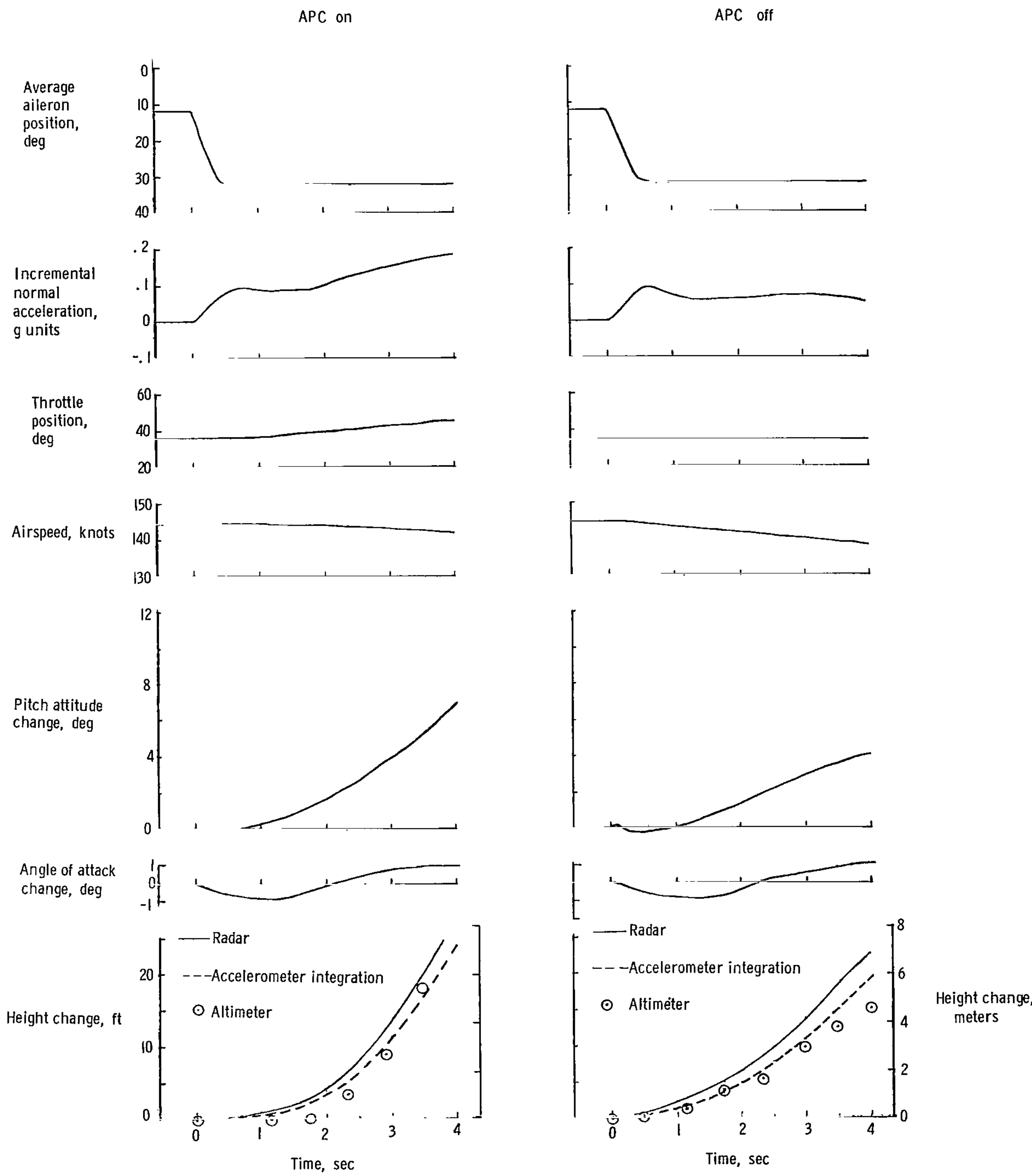
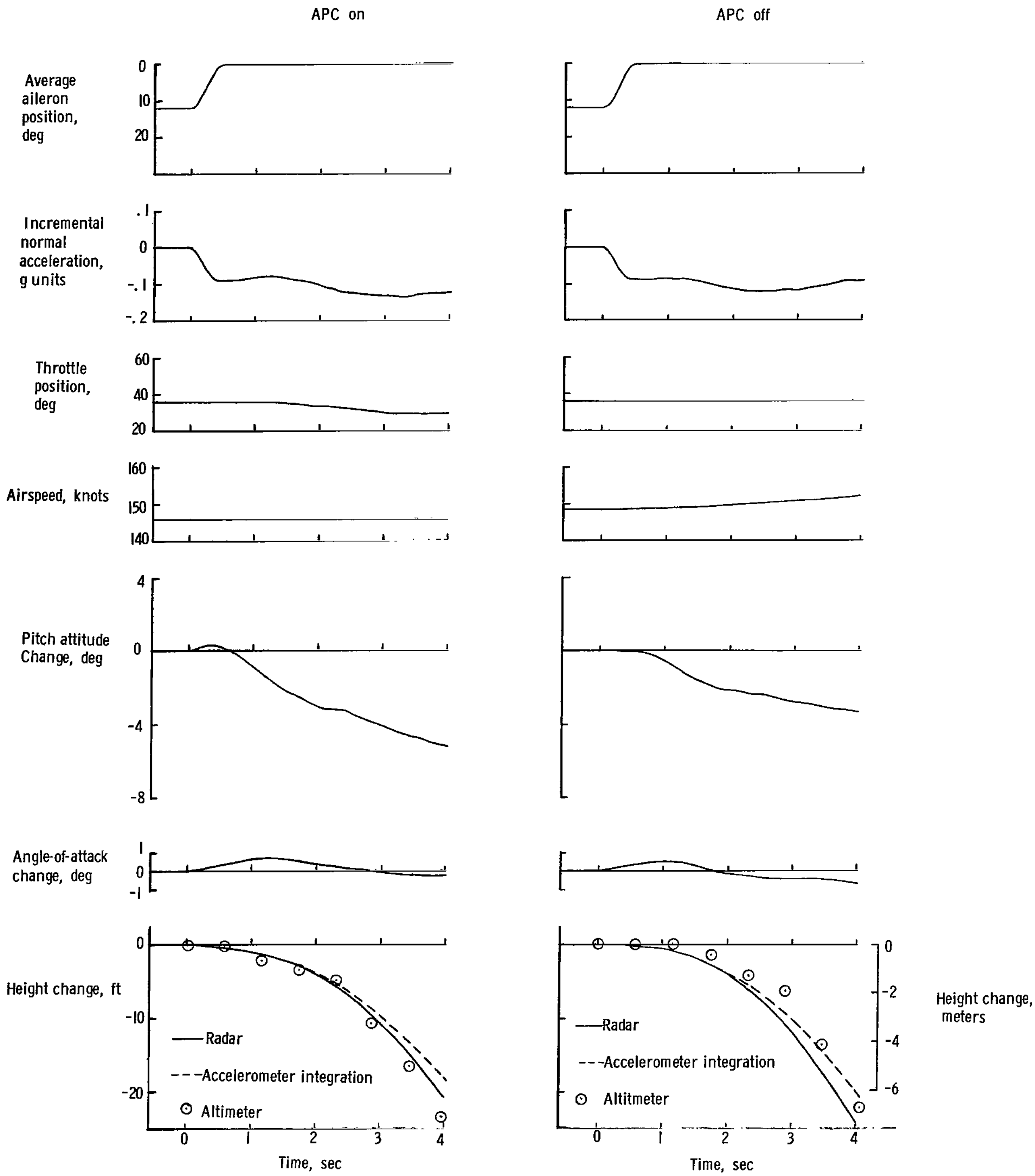


Figure 4.- Sketch of single- and double-segment landing approaches.



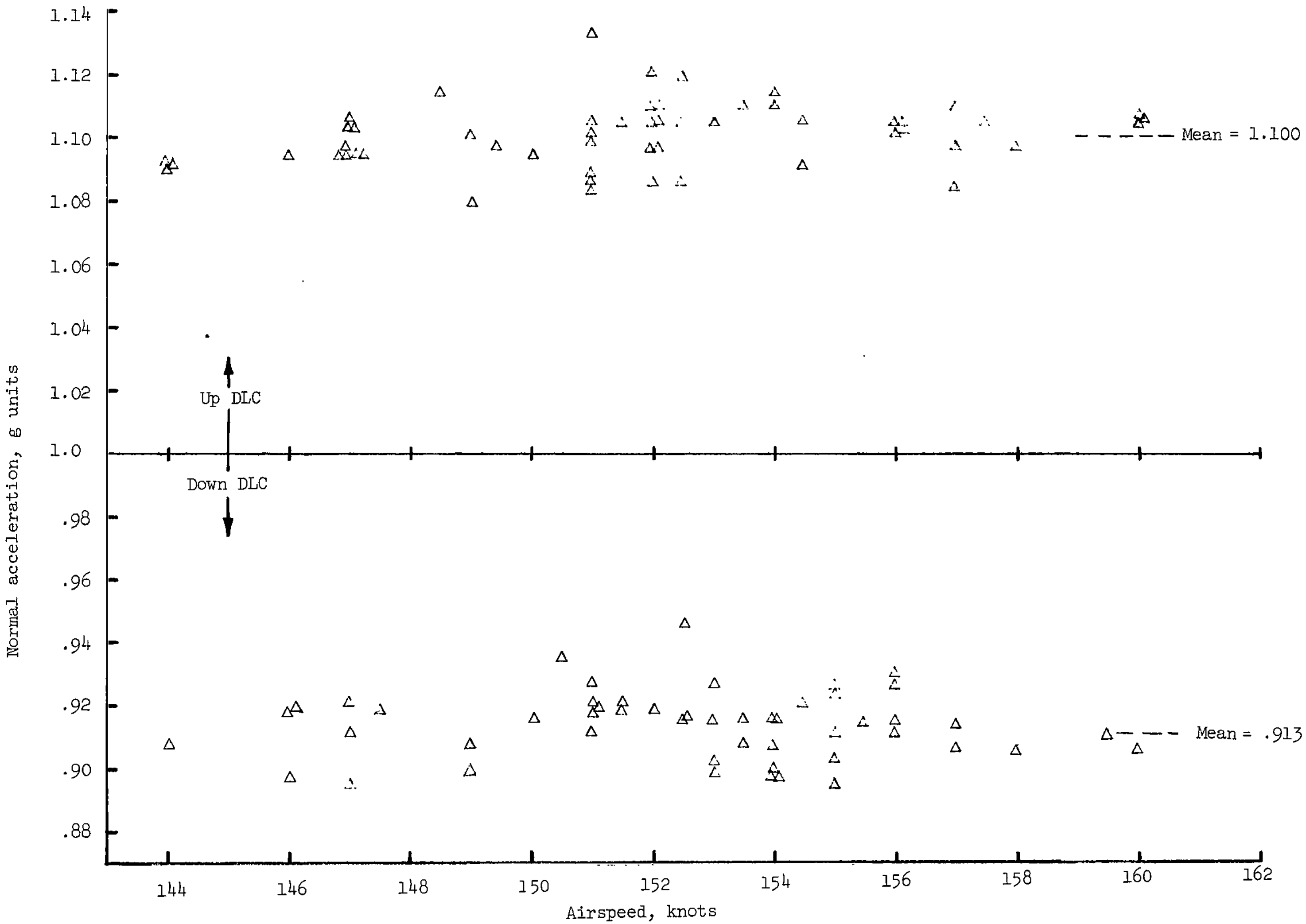
(a) Up direct lift control command.

Figure 5.- Time history response of various parameters to direct lift control inputs with and without autothrottle (APC) for an interconnect gain of 12.



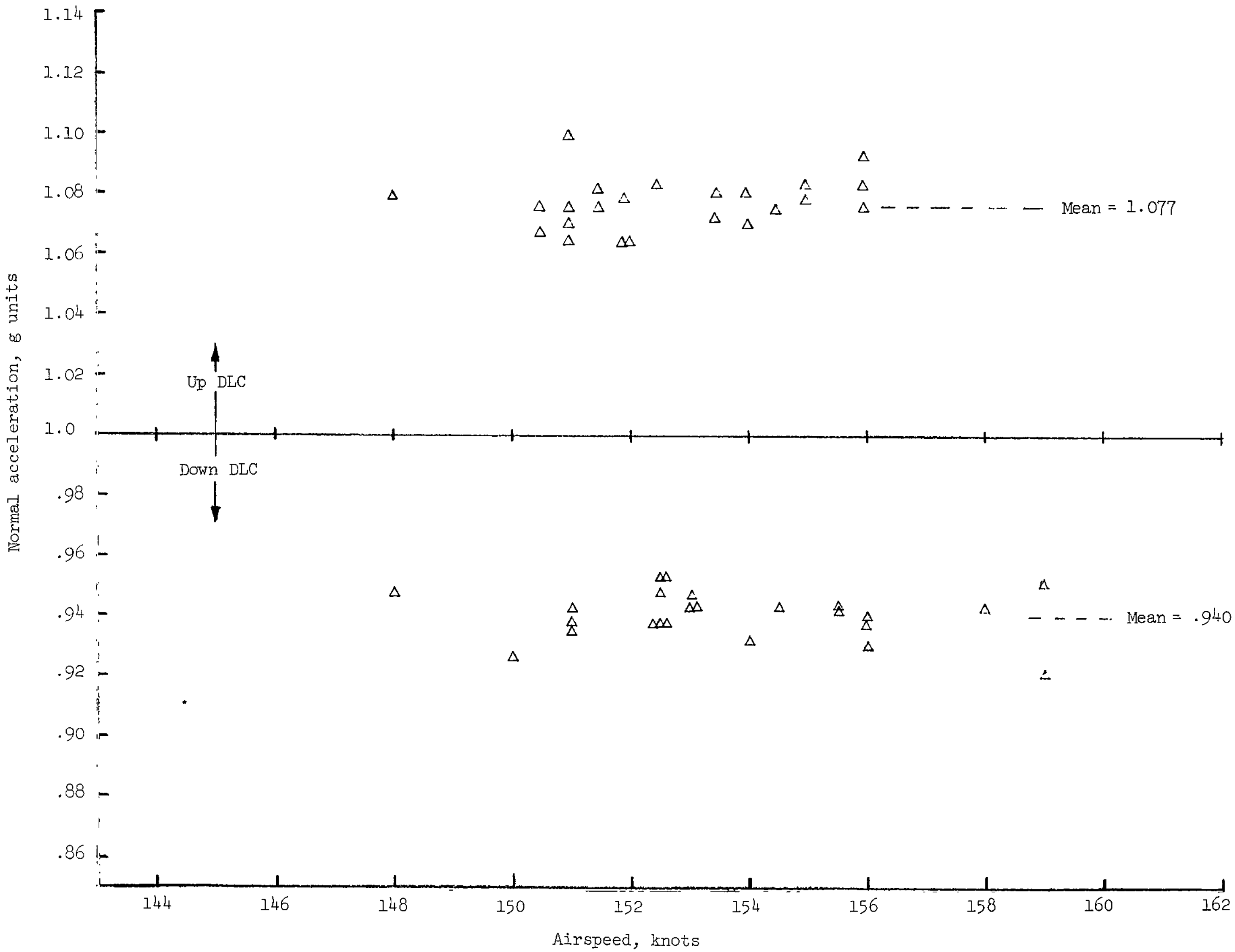
(b) Down direct lift control command.

Figure 5.- Concluded.



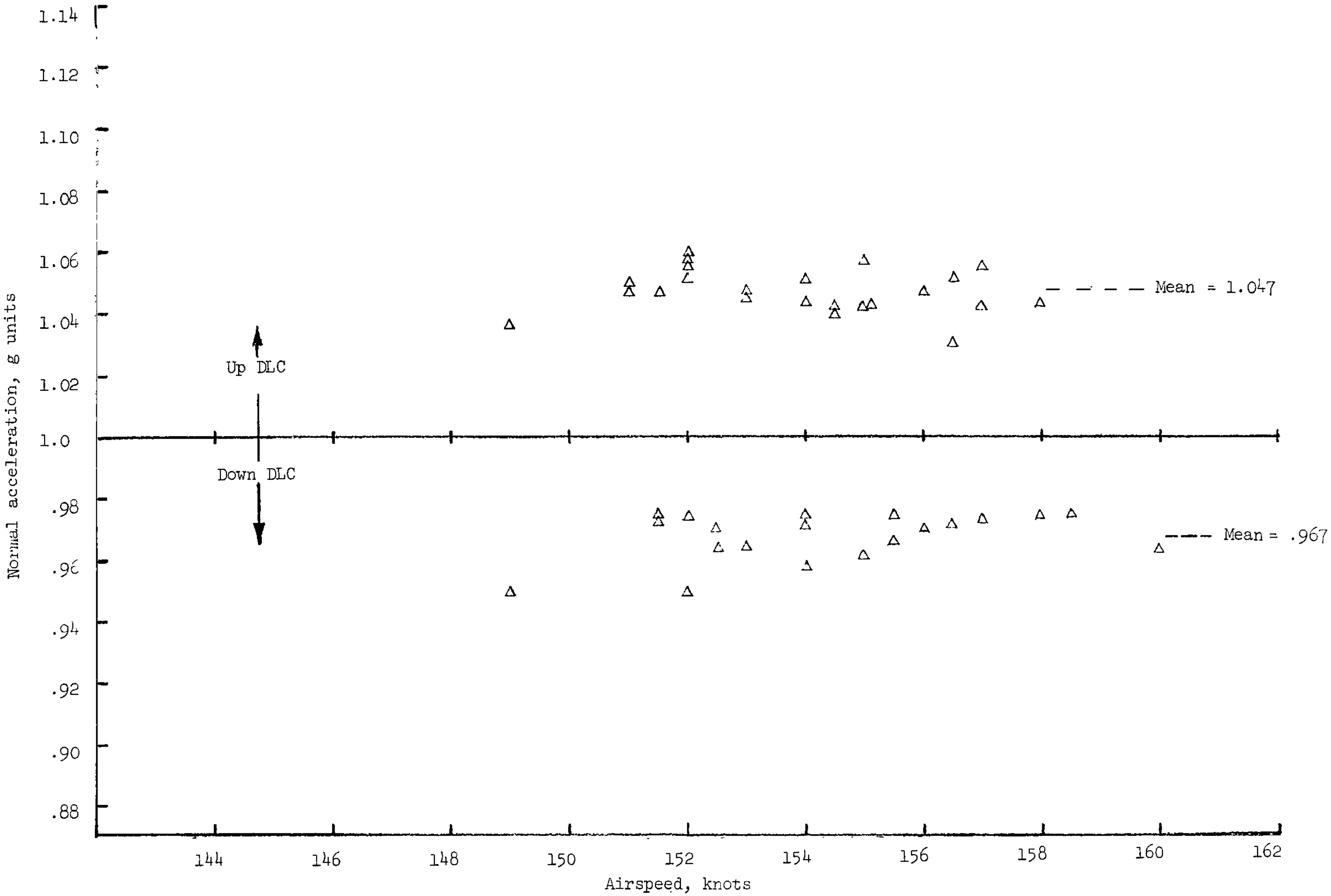
(a) Full authority.

Figure 6.- Variation with airspeed of the initial normal acceleration induced by direct lift control (DLC) inputs of full, two-thirds, and one-third authority.



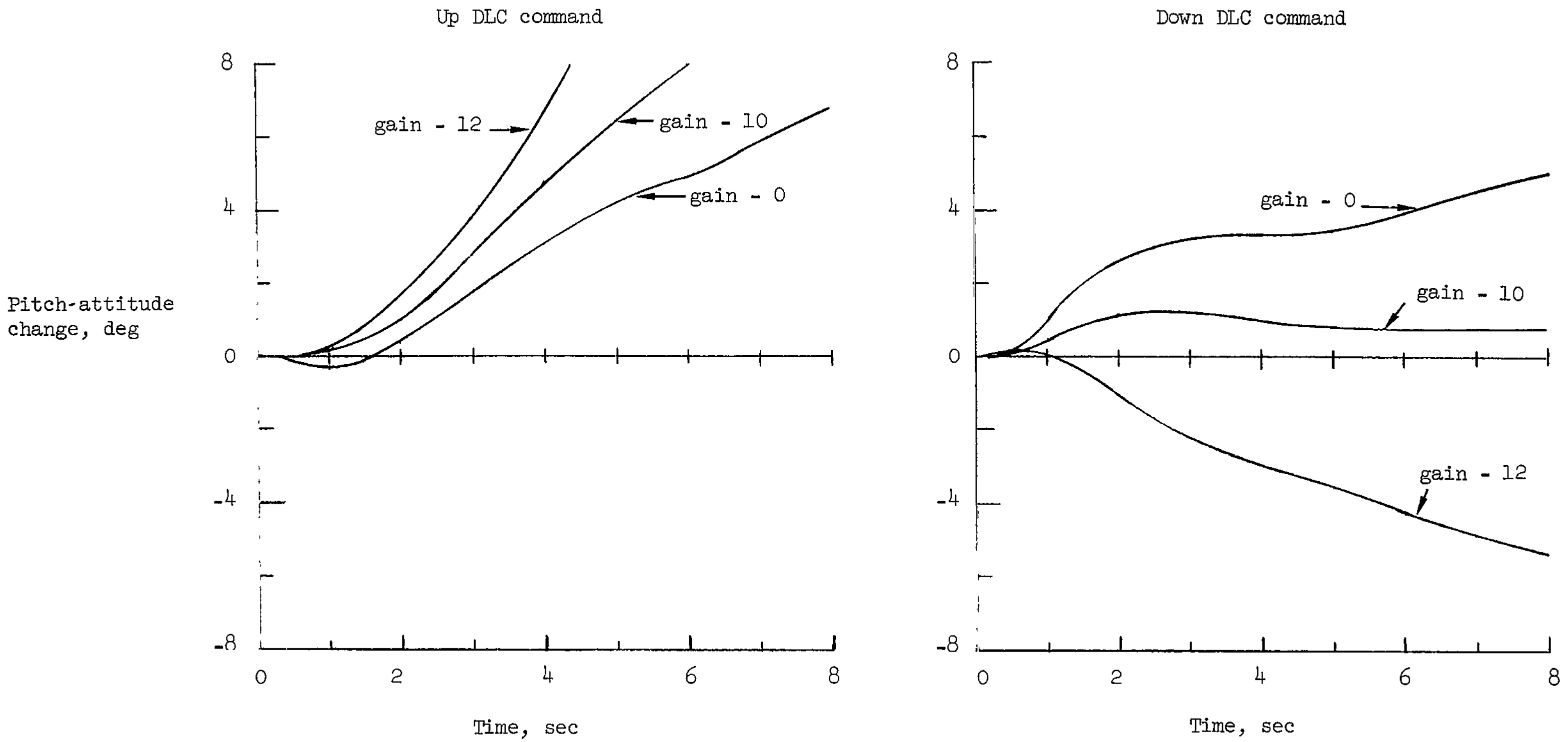
(b) Two-thirds authority.

Figure 6.- Continued.



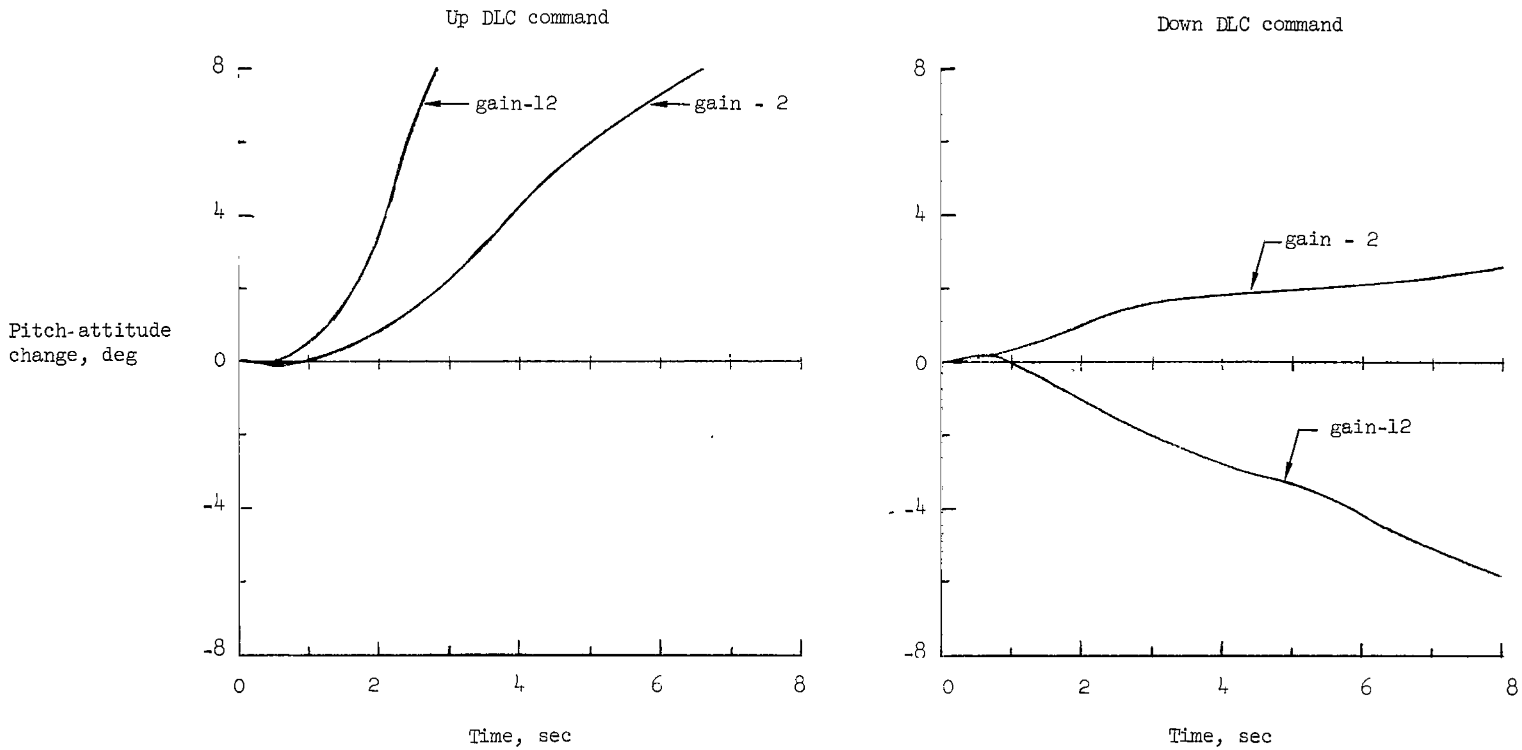
(c) One-third authority.

Figure 6.- Concluded.



(a) Forward center-of-gravity range.

Figure 7.- Pitch-attitude response to direct lift control (DLC) inputs. Full authority; autothrottle on.



(b) Aft center-of-gravity range.

Figure 7.- Concluded.

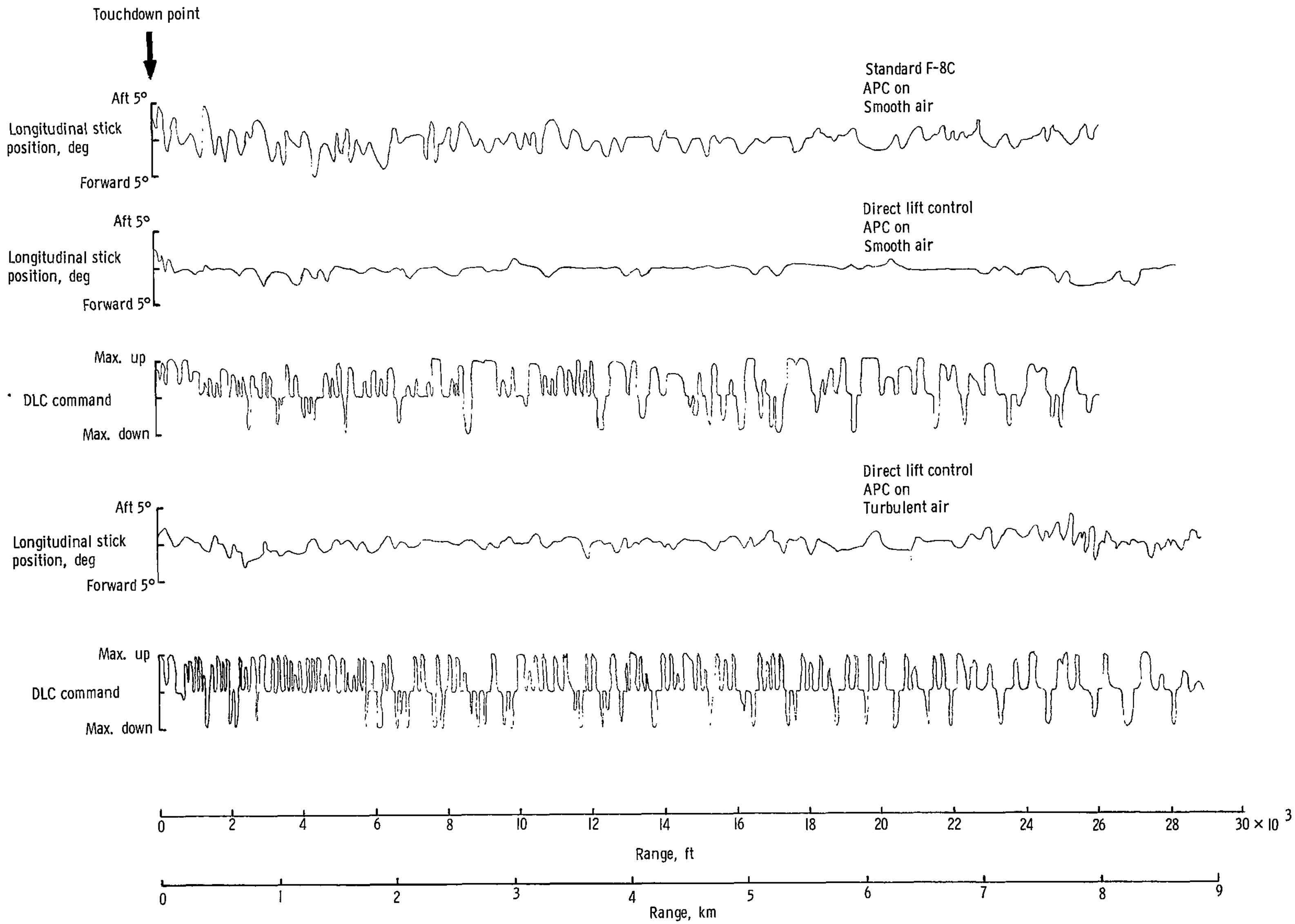


Figure 8.- Comparison of longitudinal control activity between standard and direct lift control (DLC) approaches for smooth and turbulent air.

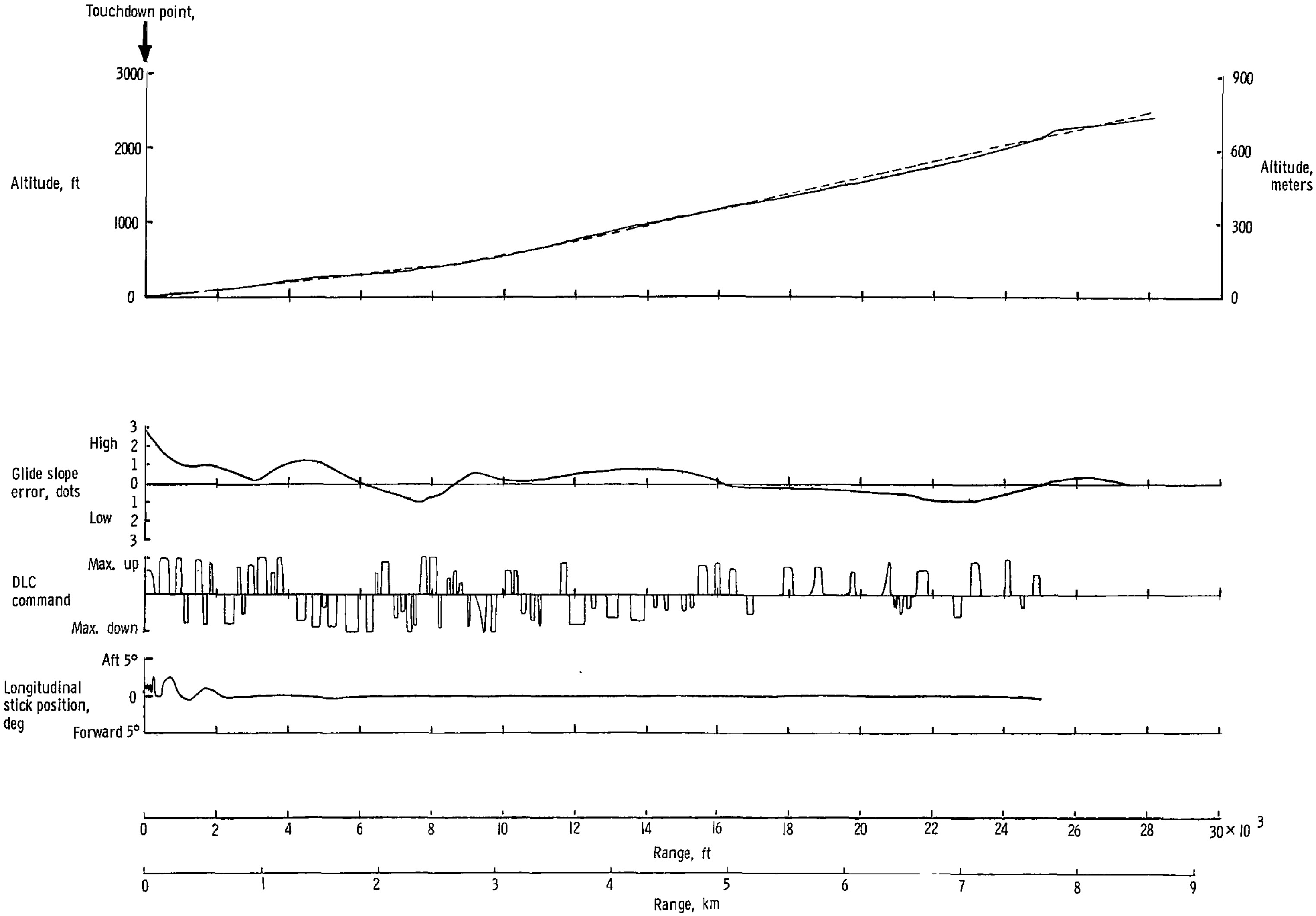
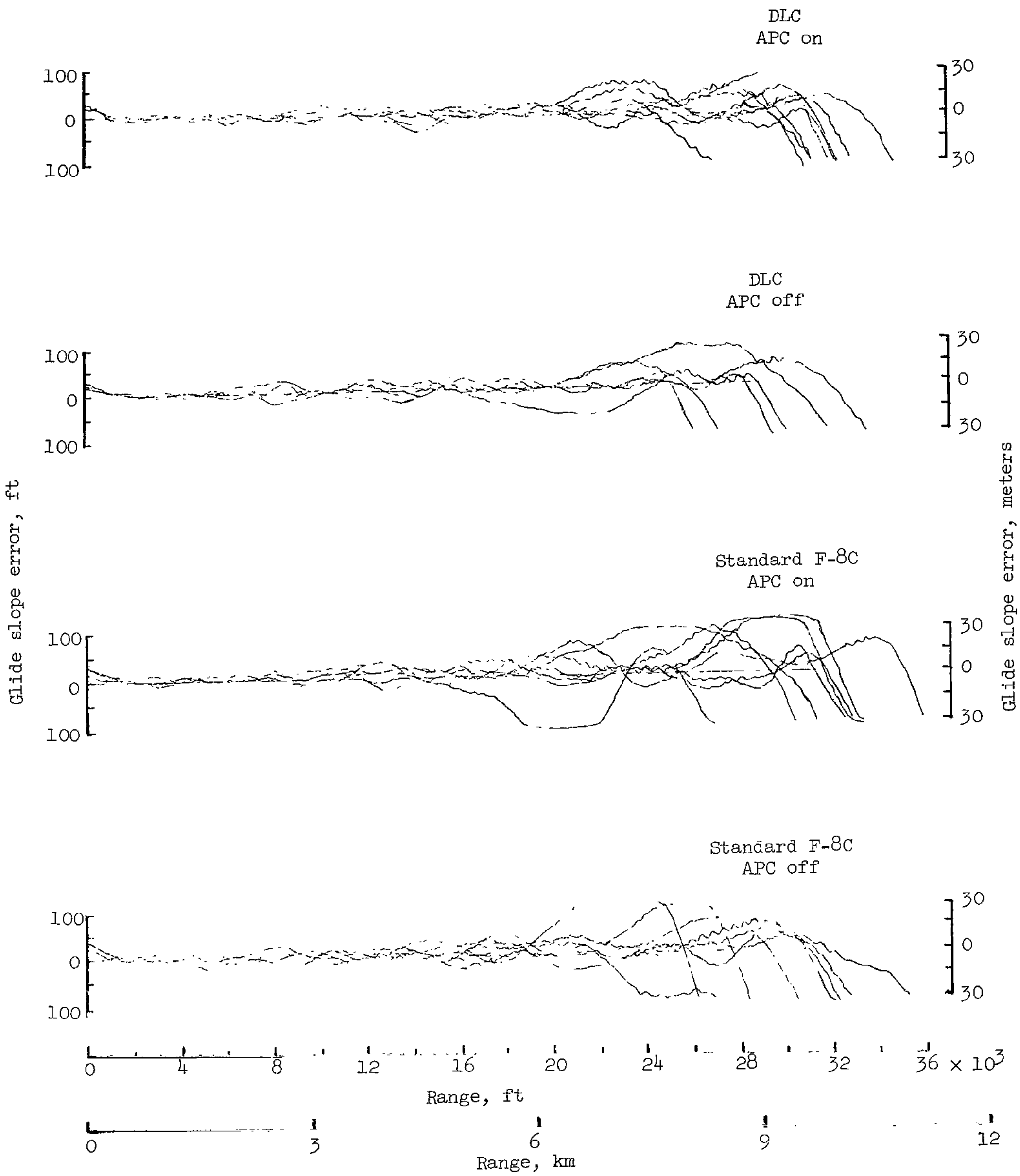
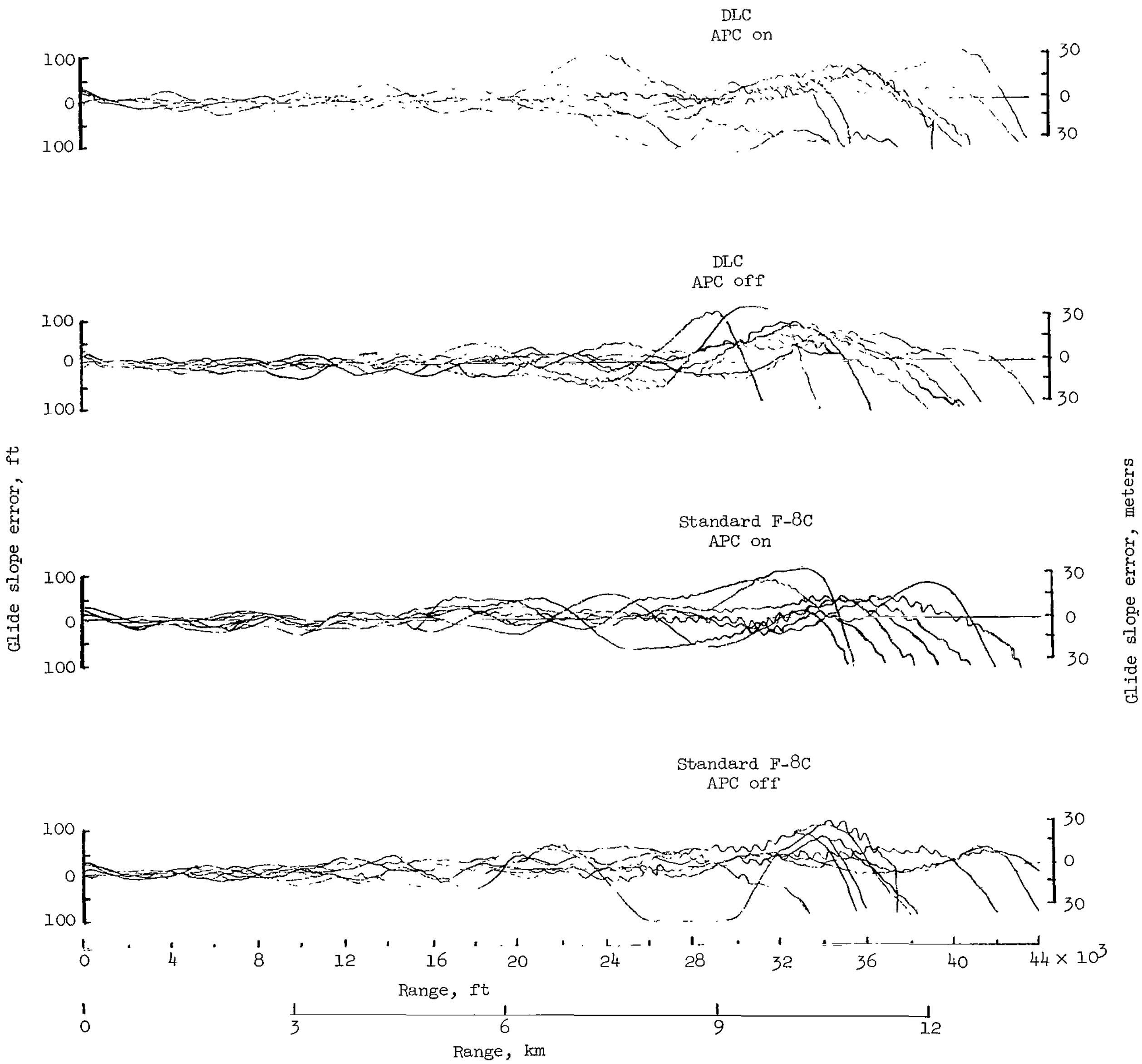


Figure 9.- Example of approach performance and longitudinal control activity with stick lock connected.



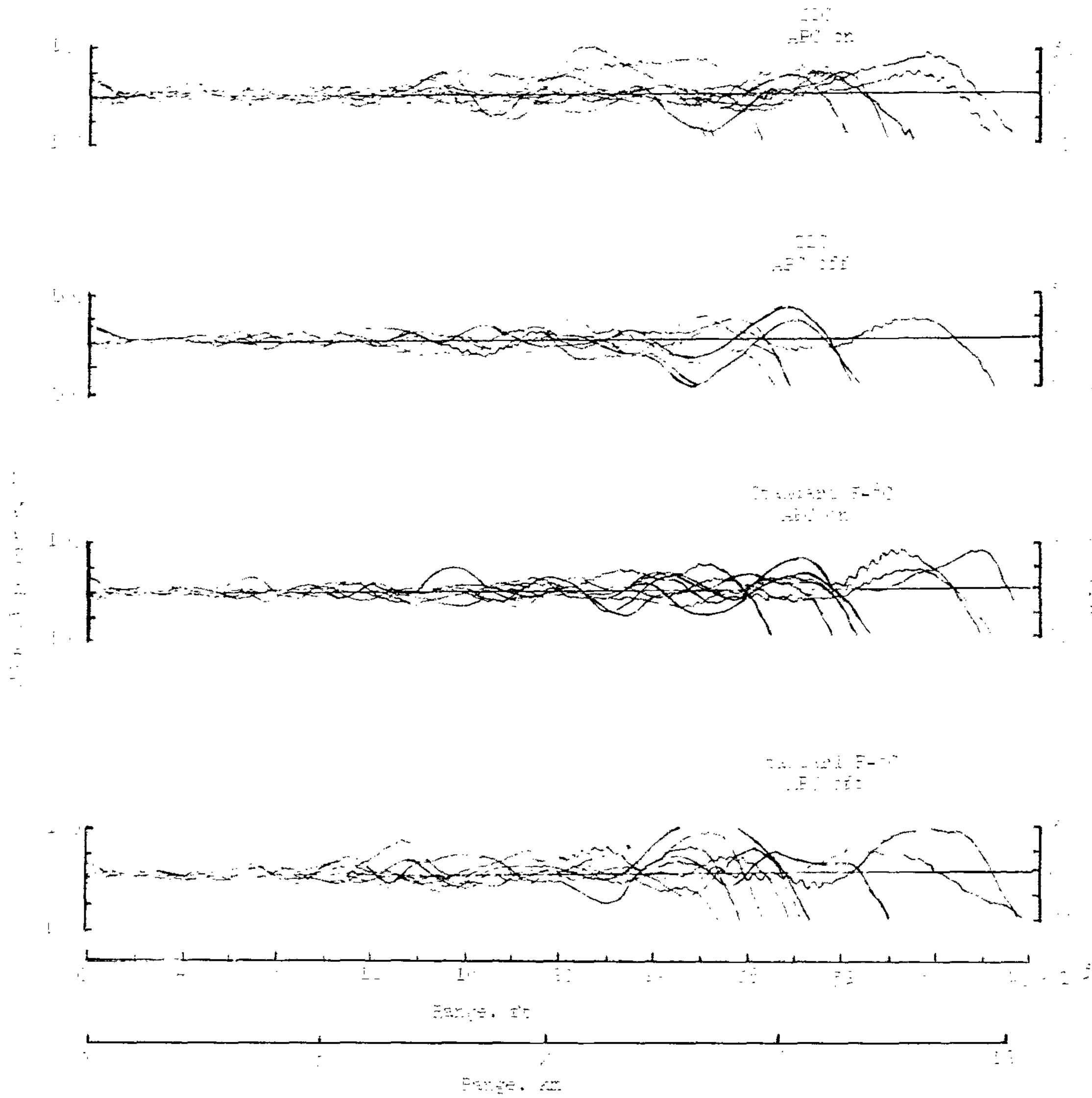
(a) Steady crosswinds, <10 knots.

Figure 10.- Time histories of glide slope error for the four configurations. APC denotes approach power compensator or autothrottle.



(b) Steady crosswinds, ≧10 knots.

Figure 10.- Continued.



(c) Turbulence.

Figure 10.- Concluded.

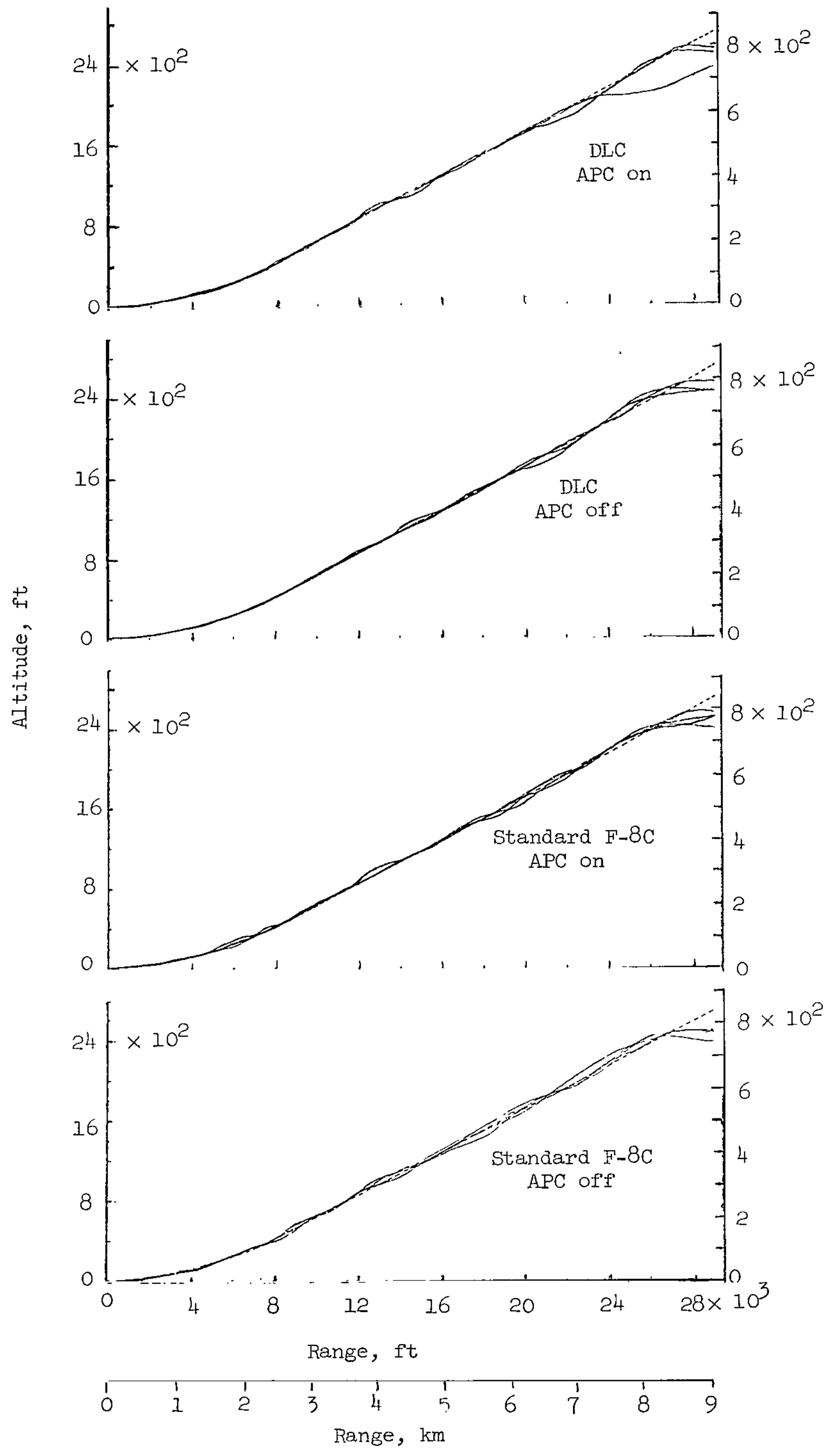


Figure 11.- Comparison of approach performance on the 6° single-segment profile for the four configurations. APC denotes autothrottle.

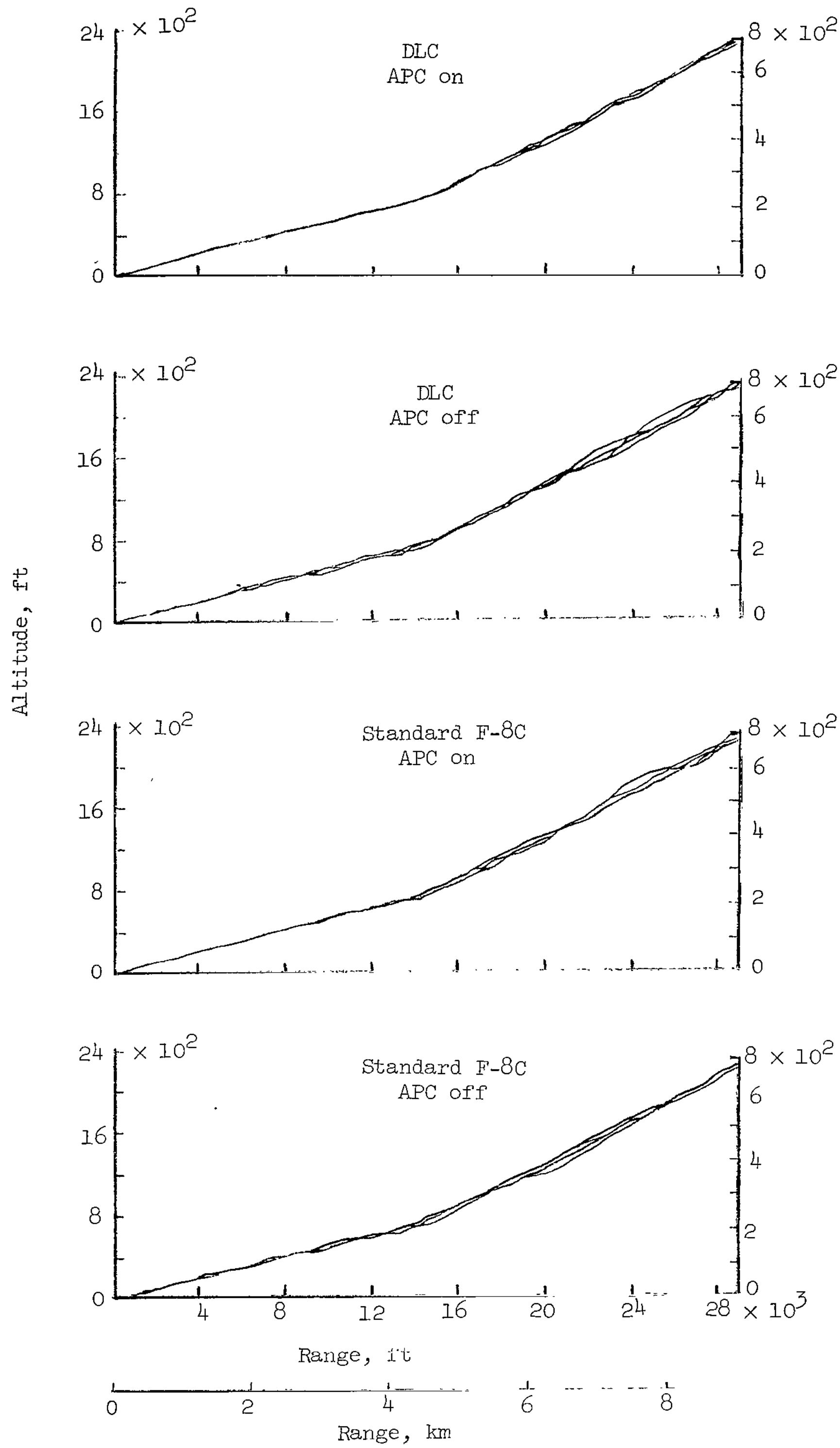


Figure 12.- Comparison of approach performance on the two-segment 6^0 into 3^0 profile for the four configurations. APC denotes autothrottle.

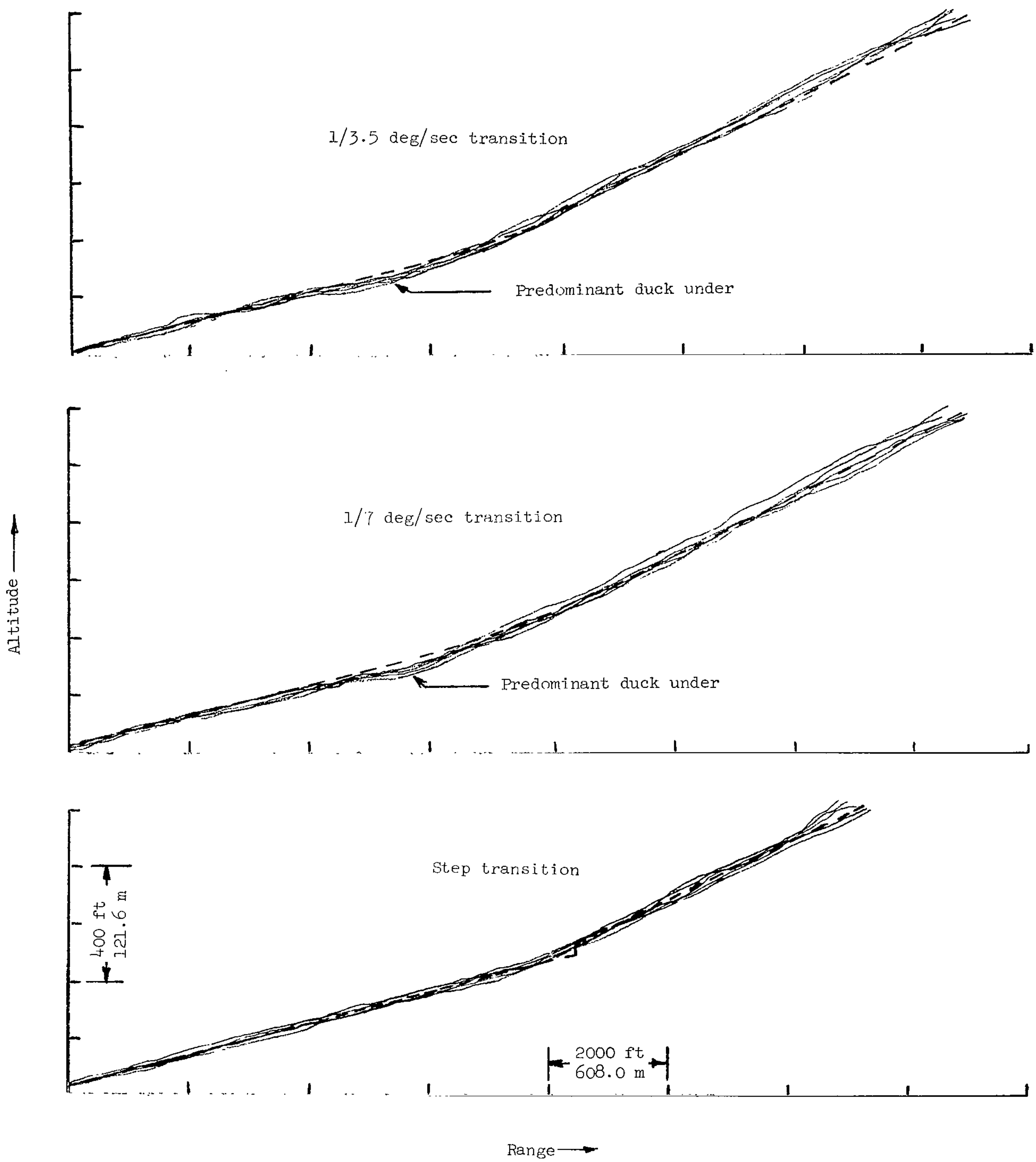


Figure 13.- Radar plots of flight-path deviations for two curved transitions and a step transition.

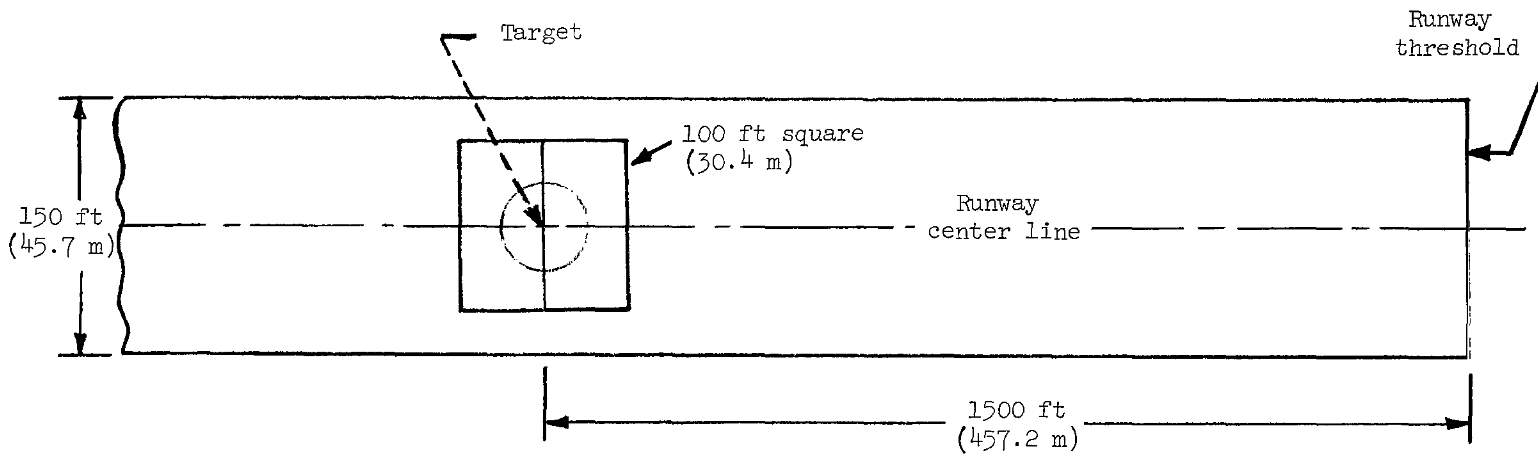
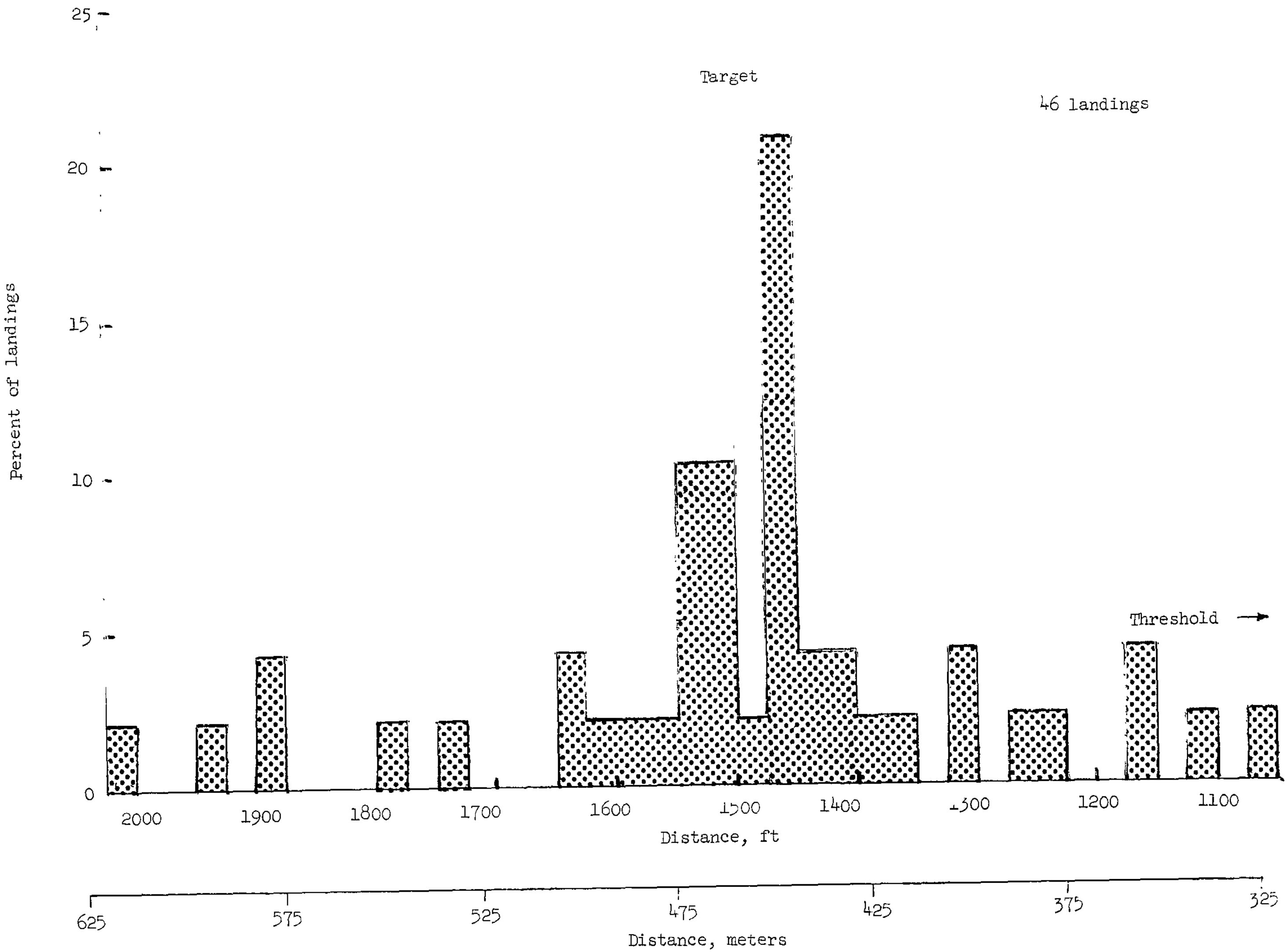
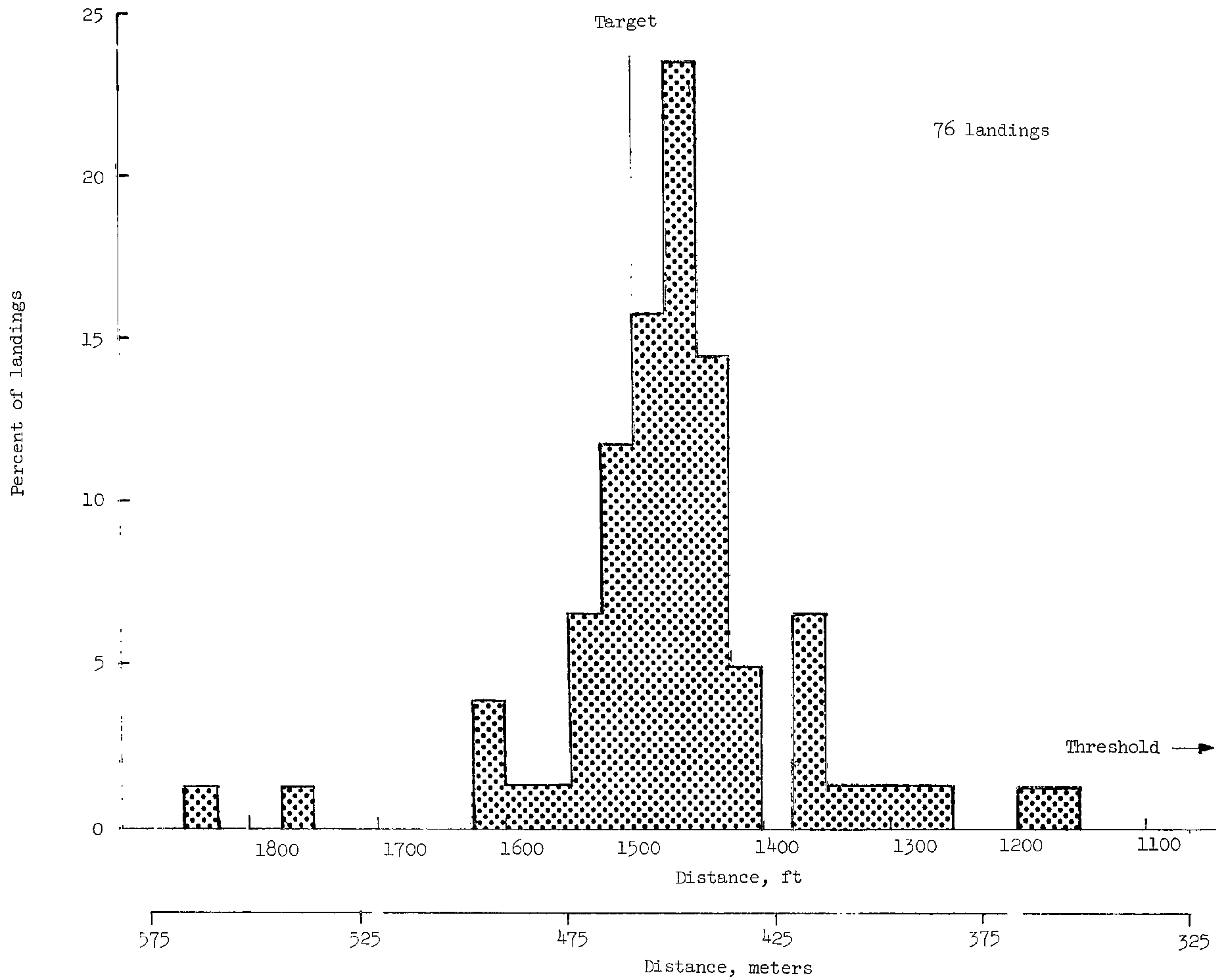


Figure 14.- Sketch of target location on runway.



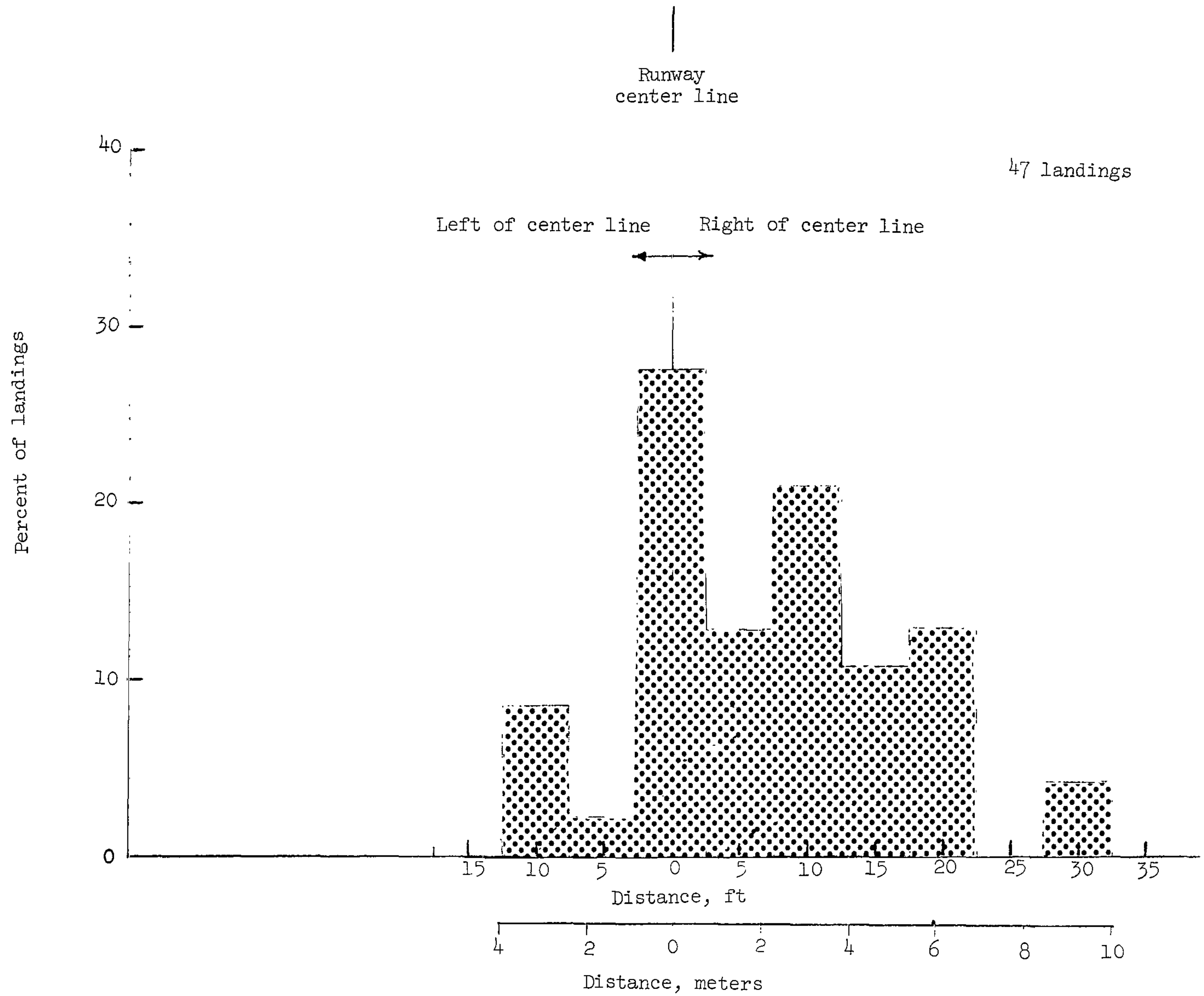
(a) Standard configuration.

Figure 15.- Frequency histogram of touchdown distance from runway threshold.



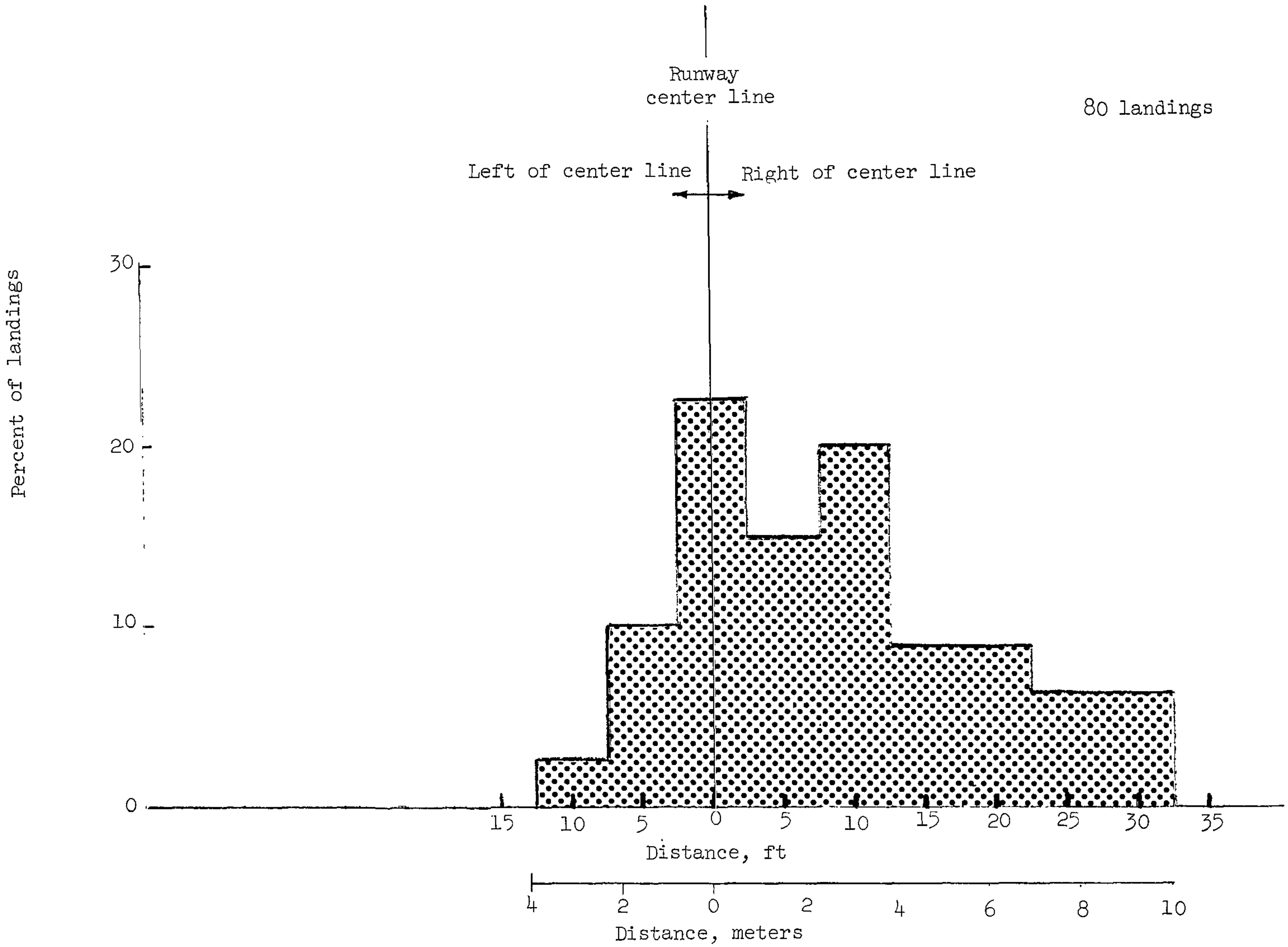
(b) Direct lift control configuration.

Figure 15.- Concluded.



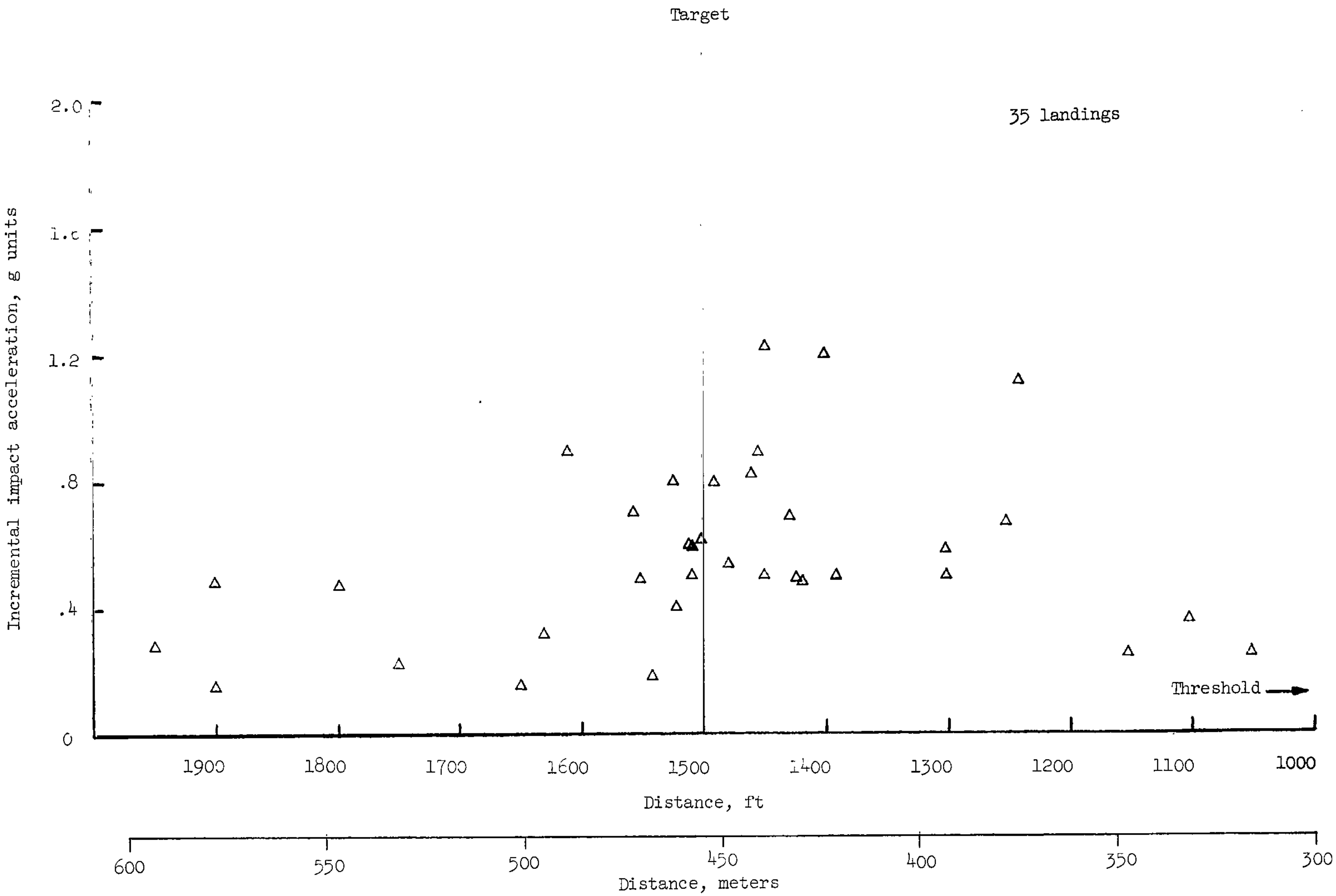
(a) Standard configuration.

Figure 16.- Frequency histogram of touchdown distance from runway center line.



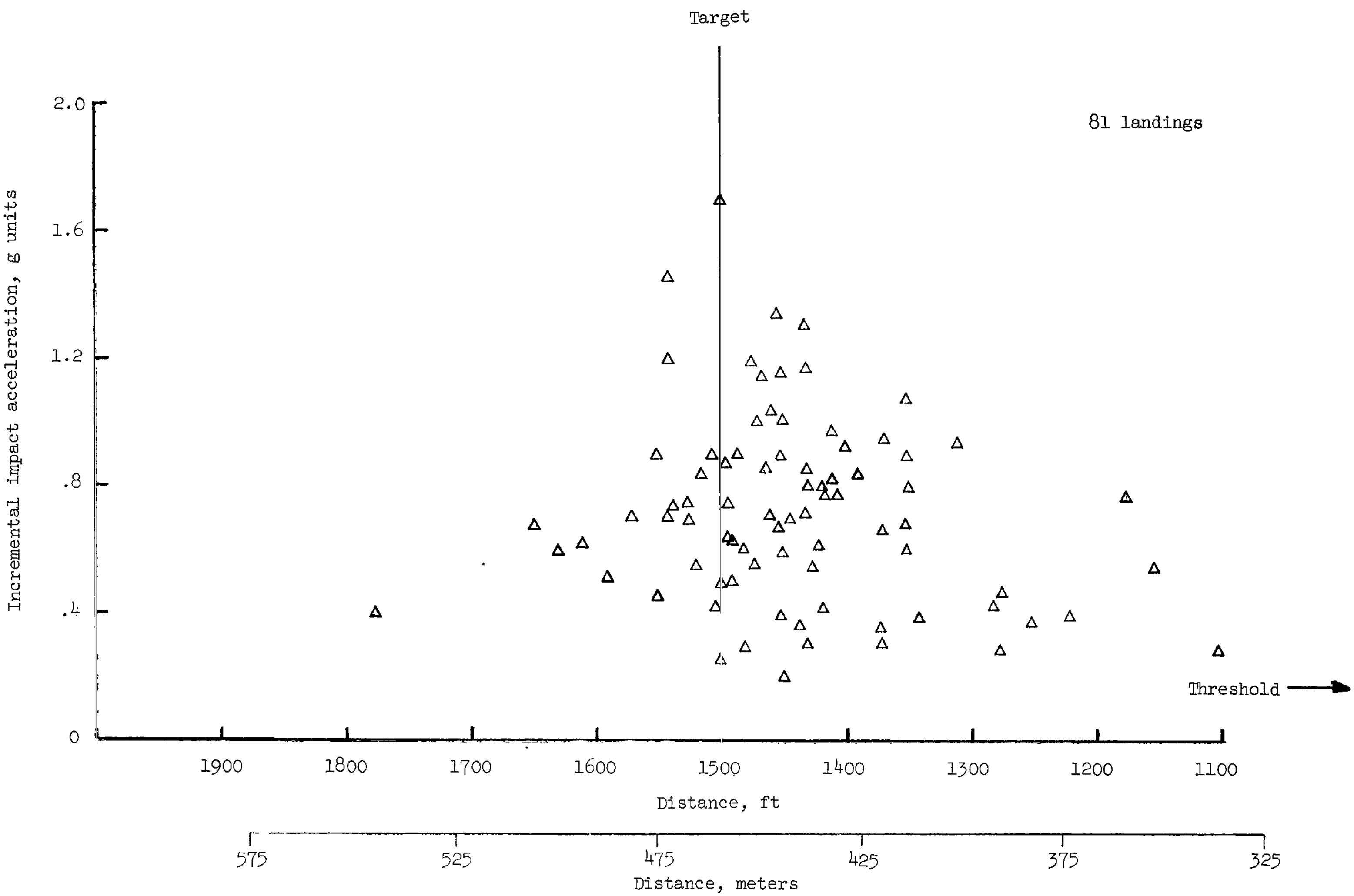
(b) Direct lift control configuration.

Figure 16.- Concluded.



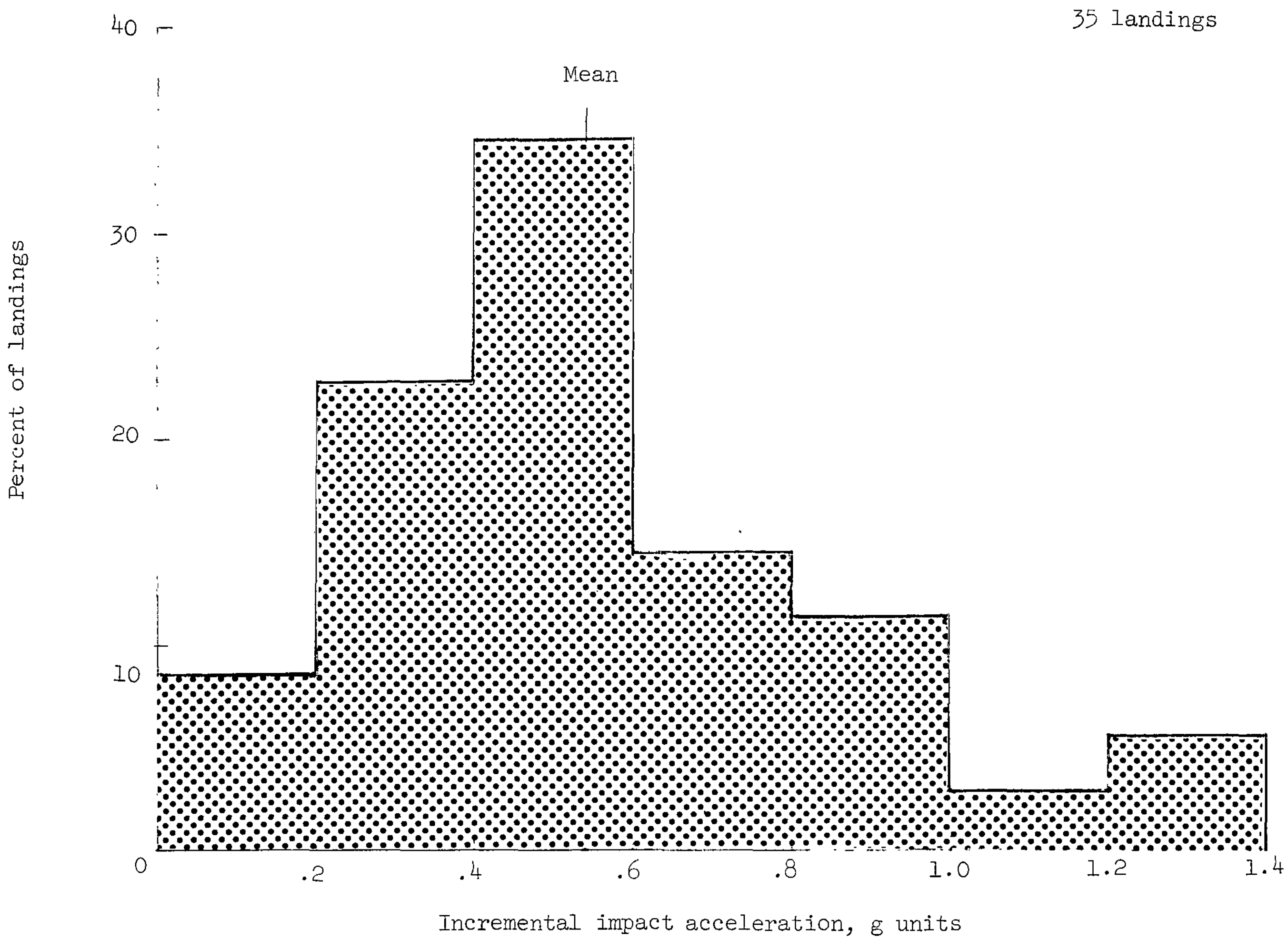
(a) Standard configuration.

Figure 17.- Variation of impact acceleration with distance from runway threshold.



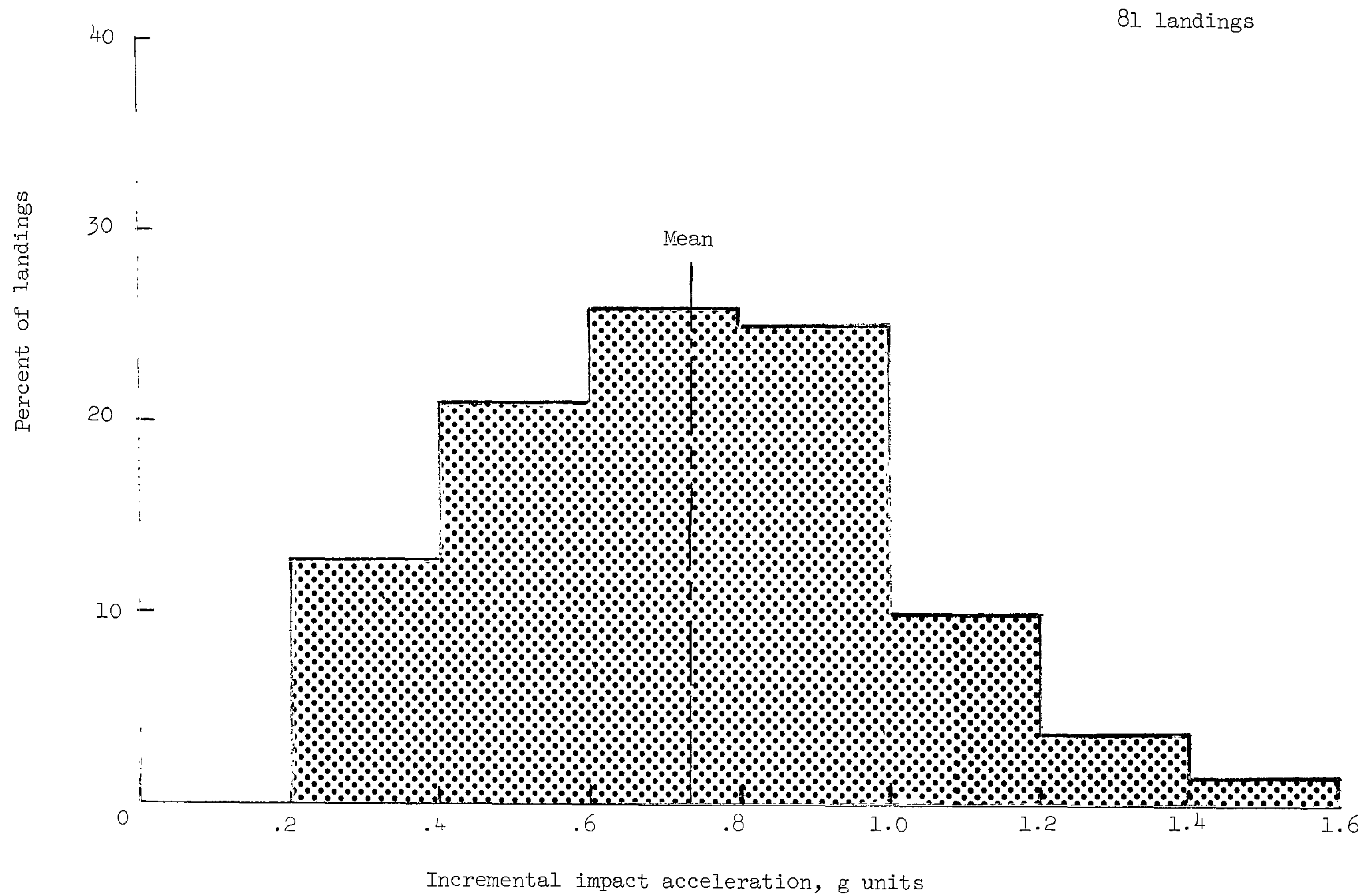
(b) Direct lift control configuration.

Figure 17.- Concluded.



(a) Standard configuration.

Figure 18.- Frequency histogram of impact acceleration for standard and direct lift control landings.



(b) Direct lift control configuration.

Figure 18.- Concluded.

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